CONTRIBUTIONS TO HAND KINEMATICS CHARACTERISATION DURING PRODUCT MANIPULATION IN ACTIVITIES OF DAILY LIVING

PhD Thesis

Castelló de la Plana
May 2021

Author
ALBA RODA SALES

Supervisors
JOAQUÍN L. SANCHO BRU
MARGARITA VERGARA MONEDERO

UNIVERSITAT
JAUME·I

UNIVERSITAT
JAUME•I

PhD Thesis

Contributions to hand kinematics characterisation during product manipulation in activities of daily living

Author
Alba Roda Sales

Supervisors
Joaquín L. Sancho Bru
Margarita Vergara Monedero

Castelló de la Plana (Spain), May 2021

Doctoral Programme in Industrial Technologies and Materials

Universitat Jaume I Doctoral School

Contributions to hand kinematics characterisation during product manipulation in activities of daily living

Report submitted by Alba Roda Sales in order to be eligible for a doctoral degree awarded by the Universitat Jaume I

Alba Roda Sales

Joaquín L. Sancho Bru

Margarita Vergara Monedero

Castelló de la Plana, May 2021

Funding

- Universitat Jaume I through the predoctoral grant PREDOC 2016/08.
- Spanish Ministry of Economy and Competitiveness through the project DPI2014-52095-P.
- Universitat Jaume I through the project P1-1B2014-10.

Abstract

The aim of this thesis is to contribute to the characterisation of hand kinematics during product manipulation in activities of daily living (ADLs), and it is the outcome of the research studies in which I have participated in the Biomechanics and Ergonomics Group of the Universitat Jaume I.

This aim is composed of three main objectives: (i) validating the use of instrumented gloves as a motion capture system for recording hand kinematics during ADLs, (ii) characterising hand kinematics in ADLs using posture and velocity-related parameters, identifying task groups requiring extreme postures or velocities, and creating a large dataset of hand kinematic data during ADLs to this purpose, and (iii) analysing the effect of assistive devices (ADs) on hand and upper limb kinematics, both using qualitative and quantitative kinematic parameters. The results presented in this thesis can be useful for researchers devoted to hand kinematics, functional assessment, rehabilitation, product design, ADs design and prescription, or to artificial intelligence applications.

A review of the state of art in the fields of product manipulation in ADLs and hand kinematic analyses is presented in order to better understand the motivation of this thesis and the gap it intended to fill with the contributions presented. Several gaps were identified: (i) few quantitative studies analysing hand joints' kinematics during product manipulation considering both posture and velocity parameters, (ii) lack of quantitative kinematic analyses considering a wide variety of product shapes, and (iii) weakness of the available kinematics datasets regarding aspects such as number of subjects studied, variety of tasks and products considered, freedom to perform the tasks in a natural way, or anatomical angles considered. Furthermore, the available systems for hand motion capture are outlined, and instrumented gloves are identified as the most appropriate technique for the recordings during product manipulation.

First, a set of studies to validate the use of instrumented gloves as a motion capture system are presented. These experiments were motivated by several concerns from previous experience of the researchers of the Biomechanics and Ergonomics Group. The studies focused on aspects such as the effect of instrumented gloves on manual skills, the feasibility of using them to measure distal interphalangeal joints, the possibility of estimating distal interphalangeal joint angles from the proximal interphalangeal ones, or the possibility of using an instrumented glove with pressure sensors to automatically distinguish free motion from manipulation in hand kinematic recordings. This chapter is intended to be a piece of advise to all researchers using instrumented gloves as a motion capture system.

After this, the KINE-ADL BE-UJI Dataset is presented, containing hand kinematic data collected from 20 healthy subjects while performing feeding and cooking ADLs, using instrumented gloves on both hands. The characteristics of this dataset are the wide variety of objects used (66 objects), the in-depth study of representative feeding and cooking tasks (58 tasks, divided into 178 actions), the freedom given to the subjects to perform the tasks, the recording of both hands and the type of data provided (continuous recording of 18 anatomical angles per hand). This dataset was made publicly available in an open repository to all the research community, being useful for applications such as hand kinematics characterisation, functional assessment, machine learning purposes or product design.

Then, tasks from the dataset were classified into several groups depending on task characteristics such as intended motion or force type. Both postural and velocity-related quantitative kinematic parameters were analysed for each task group, in order to address the observed gap in literature regarding analyses in ADLs involving product manipulation. These analyses provide an outline of the kinematic requirements of feeding and cooking tasks for a healthy population. The data provided can be considered as normative values for healthy hand kinematic performance, from which task groups that require more extreme postures or higher velocities can be identified. These task groups may be difficult to perform by people with affected hand function, thus, using or developing ADs to perform these tasks is suggested.

Finally, two experiments were carried out to fill the gap regarding the effect of ADs characteristics on hand kinematics. The first experiment consisted of visual analyses of video recordings of healthy subjects performing ADLs using normal products and ADs. Aspects such as grasp type, arm posture (shoulder, elbow and wrist) and hand-object contact zones were analysed and compared. This study provided an insight into the combined effect of products' design characteristics on hand and arm posture. The second study also consisted of the performance of ADLs using normal products and ADs, but while wearing an instrumented glove on their dominant hand. Postural and velocity-related kinematic parameters were analysed and compared, and information regarding the effects of specific characteristics of products on those parameters is provided.

In summary, the main contributions of this thesis have been: (i) providing quantifiable data of several technical aspects regarding the use of instrumented gloves for motion capture of hand kinematics during ADLs: their effect on manual skills, fitting problems, etc., (ii) providing an outline of the kinematic requirements of feeding and cooking tasks for a healthy population, identifying task groups requiring extreme postures or velocities in specific joints, as well as providing extensive data and making it available to the research community in a public repository, and (iii) presenting an overview of the effects of the design characteristics of ADs on hand kinematics, as a basis for the selection of the most suitable AD depending on the patient's impairments.

Resumen

El objetivo de esta tesis, resultado de los estudios en los que he participado en el Grupo de Biomecánica y Ergonomía de la Universitat Jaume I, es contribuir a la caracterización de la cinemática de la mano durante la manipulación de productos en actividades de la vida diaria (AVDs).

Este objetivo se compone de tres propósitos principales: (i) validar el uso de guantes instrumentados como sistema de captura de movimiento para registrar la cinemática de la mano durante las AVDs, (ii) caracterizar la cinemática de la mano en las AVDs utilizando parámetros relacionados con la postura y la velocidad, identificando grupos de tareas que requieren posturas o velocidades extremas, creando para ello una base de datos de la cinemática de la mano durante las AVDs y (iii) analizar el efecto de los dispositivos de asistencia (DAs) en la cinemática de la mano y el miembro superior mediante parámetros cinemáticos cualitativos y cuantitativos. Los resultados que se presentan en esta tesis pueden ser de utilidad para investigadores en campos como el de cinemática de la mano, evaluación funcional, rehabilitación, diseño de productos, diseño y prescripción de DAs o aplicaciones de inteligencia artificial.

En primer lugar, para entender la motivación de esta tesis e identificar el vacío que se pretende llenar con sus contribuciones, se presenta una revisión del estado del arte. Esta revisión se centra en el campo de manipulación de productos en AVDs y en el de análisis de la cinemática de la mano, en los que se identificaron las siguientes carencias: hay pocos estudios que analicen la cinemática de las articulaciones de la mano durante la manipulación de productos utilizando variedad de parámetros cinemáticos cuantitativos (especialmente parámetros relacionados con la velocidad), hay pocos trabajos en literatura analizando parámetros cinemáticos durante el uso de una amplia variedad de formas de productos y, las bases de datos de cinemática de la mano disponibles para realizar estos análisis presentan debilidades en aspectos como número de sujetos estudiados, variedad de tareas y productos considerados, libertad para realizar las tareas o ángulos anatómicos considerados. Además, se presenta una visión general de los sistemas disponibles para la captura de movimiento de la mano, identificando los guantes instrumentados como la técnica más apropiada para el registro durante manipulación de producto.

Inicialmente se presentan una serie de estudios llevados a cabo para validar el uso de guantes instrumentados como sistema de captura de movimiento. Estos experimentos fueron motivados por varias inquietudes basadas en la experiencia de los investigadores del Grupo de Biomecánica y Ergonomía, y están centrados en aspectos como el efecto de los guantes instrumentados en

la destreza manual, la viabilidad de su uso para medir articulaciones interfalángicas distales, la posibilidad de estimar los ángulos de las articulaciones interfalángicas distales a partir de las interfalángicas proximales, o la posibilidad de utilizar un guante instrumentado con sensores de presión para distinguir automáticamente el movimiento libre de la manipulación en registros de cinemática de la mano. Este capítulo pretende servir de apoyo a todos los investigadores que utilizan guantes instrumentados como sistema de captura de movimiento.

A continuación, se presenta la base de datos KINE-ADL BE-UJI Dataset, compuesta por datos de la cinemática de la mano de 20 sujetos sanos mientras realizaban AVDs de cocina y alimentación mientras llevaban puestos guantes instrumentados en ambas manos. Las características más destacadas de esta base de datos son la amplia variedad de objetos utilizados (66 objetos), el detalle con el que se han estudiado las tareas representativas de cocina y alimentación (58 tareas, divididas en 178 acciones), la libertad dada a los sujetos para realizar las tareas, el hecho de registrar ambas manos y tipo de datos proporcionados (registro continuo de 18 ángulos anatómicos por mano). Este conjunto de datos está publicado en un repositorio abierto accesible para cualquier investigador, siendo útil para aplicaciones como caracterización cinemática de la mano, evaluación funcional, machine learning o diseño de productos.

Después de ello, las tareas de la base de datos se clasificaron en varios grupos en función de características como el movimiento previsto o el tipo de fuerza ejercida. Para cada grupo de tareas se analizaron parámetros cinemáticos cuantitativos relacionados tanto con la postura como con la velocidad, con el fin de abordar la falta de análisis cinemáticos durante la manipulación de productos en AVDs. Estos análisis proporcionan una visión global de los requisitos cinemáticos de las tareas de cocina y alimentación para sujetos sanos. Los datos proporcionados pueden ser considerados valores de normalidad de la cinemática de la mano sana, donde pueden identificarse grupos de tareas que requieren posturas más extremas o velocidades más altas. Dichas tareas identificadas pueden ser difícilmente realizadas por personas con mermas en la funcionalidad de la mano, por lo que se sugiere el uso y desarrollo de DAs para la realización de las mismas.

Finalmente, se llevaron a cabo dos experimentos para abordar la falta de trabajos en literatura que analicen el efecto de las características de los DAs en la cinemática de la mano. El primer estudio consistió en el análisis visual de vídeos de sujetos sanos durante la realización de AVDs con productos normales y DAs. Aspectos como el tipo de agarre, la postura del brazo (hombro, codo y muñeca) y las zonas de contacto mano-objeto fueron analizados y comparados. Con este estudio se proporciona una visión global del efecto combinado que tiene la forma de los productos en la postura de las manos y los brazos. El segundo estudio también consistió en la realización de AVDs utilizando productos normales y DAs, pero en este caso se realizaron registros con un guante instrumentado en la mano dominante de los sujetos. En este estudio se analizan y comparan parámetros cinemáticos relacionados con la postura y la velocidad, proporcionando información sobre el efecto de las características de los productos sobre dichos parámetros.

En resumen, las principales contribuciones de esta tesis han sido: (i) proporcionar datos cuantificables sobre diversos aspectos técnicos del uso de guantes instrumentados como sistema de captura de movimiento en AVDs: su efecto en la destreza manual, problemas de ajuste a la mano, etc., (ii) presentar en líneas generales los requisitos cinemáticos de las tareas de alimentación y cocina en la mano sana, identificando grupos de tareas que requieren posturas o velocidades extremas en articulaciones específicas, así como proporcionar una base de datos extensa y ponerla a disposición de la comunidad científica en un repositorio público, y (iii) presentar una visión general del efecto de las características de los DAs en la cinemática de la mano, proporcionando una base para la selección del DA más apropiado en función de los impedimentos del paciente.

Resum

L'objectiu d'aquesta tesi, resultat dels estudis en els quals he participat en el Grup de Biomecànica i Ergonomia de la Universitat Jaume I, és contribuir a la caracterització de la cinemàtica de la mà durant la manipulació de productes en activitats de la vida diària (AVDs).

Aquest objectiu es compon de tres propòsits principals: (i) validar l'ús de guants instrumentats com a sistema de captura de moviment per al registre de la cinemàtica de la mà durant les AVDs, (ii) caracteritzar la cinemàtica de la mà durant les AVDs mitjançant paràmetres relacionats amb la postura i la velocitat, identificant grups de tasques que requereixen postures o velocitats extremes, creant per a això una base de dades de la cinemàtica de la mà durant les AVDs i (iii) analitzar l'efecte dels dispositius d'assistència (DAs) en la cinemàtica de la mà i el membre superior mitjançant paràmetres qualitatius i quantitatius. Els resultats que es presenten en aquesta tesi poden ser d'utilitat per a investigadors en camps com el de cinemàtica de la mà, avaluació funcional, rehabilitació, disseny de productes, disseny i prescripció de DAs o aplicacions d'intel·ligència artificial.

En primer lloc, per tal d'entendre la motivació d'aquesta tesi i identificar el buit que es pretén cobrir amb les seues contribucions, es presenta una revisió de l'estat de l'art. Aquesta revisió es centra en el camp de manipulació de productes en AVDs i en el d'anàlisi de la cinemàtica de la mà, en els quals es van identificar les següents carències: hi ha pocs estudis que analitzen la cinemàtica de les articulacions de la mà durant la manipulació de productes utilitzant una àmplia varietat de paràmetres cinemàtics quantitatius (especialment paràmetres relacionats amb la velocitat), hi ha pocs treballs en literatura analitzant paràmetres cinemàtics durant l'ús d'una extensa varietat de formes de productes i, les bases de dades de cinemàtica de la mà disponibles per a realitzar aquestes anàlisis presenten febleses en aspectes com ara el nombre de subjectes estudiats, la varietat de tasques i productes considerats, la llibertat per a fer les tasques o els angles anatòmics considerats. A més, es presenten en línies generals els sistemes disponibles per a la captura de moviment de la mà, identificant els guants instrumentats com la tècnica més apropiada per al registre durant la manipulació de productes.

Inicialment es presenten una sèrie d'estudis realitzats per tal de validar l'ús de guants instrumentats com a sistema de captura de moviment. Aquests experiments van ser motivats per diverses inquietuds basades en l'experiència dels investigadors del Grup de Biomecànica i Ergonomia, i estan centrats en aspectes com ara l'efecte dels guants instrumentats en la destresa

manual, la viabilitat del seu ús per a mesurar articulacions interfalàngiques distals, la possibilitat d'estimar els angles de les articulacions interfalàngiques distals a partir de les interfalàngiques proximals, o la possibilitat d'utilitzar un guant instrumentat amb sensors de pressió per tal de distingir automàticament el moviment lliure de la manipulació en enregistraments de cinemàtica de la mà. Aquest capítol pretén servir de suport a tots els investigadors que utilitzen guants instrumentats com a sistema de captura de moviment.

A continuació, es presenta la base de dades KINE-ADL BE-UJI Dataset, la qual conté dades de la cinemàtica de la mà de 20 subjectes sans mentre realitzaven AVDs de cuina i alimentació mentre portaven posats guants instrumentats en ambdues mans. Les característiques més destacades d'aquesta base de dades són l'àmplia varietat d'objectes utilitzats (66 objectes), el detall amb el qual s'han estudiat les tasques representatives de cuina i alimentació (58 tasques, dividides en 178 accions), la llibertat donada als subjectes per a fer les tasques, el fet de registrar ambdues mans i el tipus de dades proporcionades (registre continu de 18 angles anatòmics per mà). Aquest conjunt de dades està publicat en un repositori obert accessible per a qualsevol investigador, i pot ser útil per a aplicacions com ara caracterització cinemàtica de la mà, avaluació funcional, machine learning o disseny de productes.

Després d'això, les tasques de la base de dades es van classificar en diversos grups en funció de característiques com ara el moviment previst o el tipus de força exercida. Per a cada grup de tasques es van analitzar paràmetres cinemàtics quantitatius relacionats tant amb la postura com amb la velocitat, amb la finalitat d'abordar la falta d'anàlisis cinemàtics durant la manipulació de productes en AVDs. Aquestes anàlisis proporcionen una visió en línies generals dels requisits cinemàtics de les tasques d’alimentació i cuina en la població sana. Les dades proporcionades poden considerar-se valors de normalitat de la cinemàtica de la mà sana, en els quals poden identificar-se grups de tasques que requereixen postures més extremes o velocitats més altes. Aquestes tasques identificades difícilment podrien ser realitzades per persones amb funcionalitat de la mà reduïda, per la qual cosa es suggereix l'ús i disseny de DAs per a la realització d'aquestes.

Finalment, es van dur a terme dos experiments per tal d’abordar la falta de treballs en literatura que analitzen l'efecte de les característiques dels DAs en la cinemàtica de la mà. El primer estudi va consistir en l'anàlisi visual de vídeos de subjectes sans durant la realització d’AVDs amb productes normals i DAs. Aspectes com el tipus d’agafada, la postura del braç (muscle, colze i canell) i les zones de contacte mà-objecte van ser analitzats i comparats. Amb aquest estudi es proporciona una visió global de l'efecte combinat que té la forma dels productes en la postura de les mans i els braços. El segon estudi també va consistir en la realització d’AVDs utilitzant productes normals i DAs, però en aquest cas es van realitzar registres amb un guant instrumentat a la mà dominant dels subjectes. En aquest estudi s'analitzen i comparen paràmetres cinemàtics relacionats amb la postura i la velocitat, proporcionant informació sobre l'efecte de les característiques dels productes sobre aquests paràmetres.

En resum, les principals contribucions d'aquesta tesi han sigut: (i) proporcionar dades quantificables sobre diversos aspectes tècnics de l'ús de guants instrumentats com a sistema de captura de moviment en AVDs: el seu efecte en la destresa manual, problemes d'ajust a la mà, etc., (ii) presentar en línies generals els requisits cinemàtics de les tasques d'alimentació i cuina per a la mà sana, identificant grups de tasques que requereixen postures o velocitats extremes en articulacions específiques, així com proporcionar una base de dades extensa i posar-la a disposició de la comunitat científica en un repositori públic, i (iii) presentar una visió general de l'efecte de les característiques dels DAs en la cinemàtica de la mà, proporcionant una base per a la selecció del DA més apropiat en funció dels impediments del pacient.

Agraïments

No és gens fàcil expressar en unes línies tot l'agraïment que voldria transmetre a totes les persones que han estat donant-me suport durant tots aquests anys i que, d'alguna manera, formen part d'aquesta tesi.

En primer lloc voldria agrair als meus directors de tesi, Ximo i Marga, tota la seua dedicació i paciència. El seu suport tant a nivell laboral com personal ha sigut imprescindible per poder dur a terme aquesta tesi. Gràcies per haver confiat en mi i haver-me donat l'oportunitat de formar-me al vostre costat. Així mateix, voldria donar les gràcies a tots els companys del Grup de Biomecànica i Ergonomia i de l'Àrea d'Expressió Gràfica en l'Enginyeria, especialment als meus companys Vero, Néstor, Vicent i Quique per haver estat sempre ahí per a tot, tant els dies bons com els no tant bons. Pels seus consells, per la seua ajuda i, sobre tot, pel seu suport a nivell anímic. Voldria agrair també a Sonia Buralla, Miguel Jiménez i Marina Cañadas la seva ajuda per a la realització dels experiments al laboratori, així com a totes les persones que van participar en els experiments de manera desinteressada.

Gràcies també a Jon Sanford i a tots els membres del Center for Inclusive Design and Innovation del Georgia Institute of Technology per acollir-me durant el període en el qual vaig realitzar l'estada i permetre'm aprendre al seu costat. I, especialment, gràcies a Adriana Weinberg i Marc Esquerrà. La meva estada a Atlanta no haguera sigut el mateix sense ells dos.

També voldria agrair a tots els meus amics i amigues tota la seva paciència durant aquest període, en especial a Eva, Sandra i Irene, que han estat sempre de manera incondicional en els moments més difícils. A Xavi pel seu suport des del primer dia en tot allò que he emprés, tot i la distància. A Miquel Àngel, que tot i ser el pitjor professor de mallorquí que he conegut, m'ha tret sempre un somriure quan més ho he necessitat. A Belén i Víctor per tots els bons moments que hem compartit. A Alberto per tota la seva ajuda en aquest trajecte final de la tesi, que tant necessitava.

Agraïment molt especial a tota la meva família, tant als qui estan com als qui ja no estan. Gràcies per haver confiat en mi des del primer moment. Gràcies per haver-me animat quan s'esgotaven les forces. No crec que trobe les paraules adients per tal d'expressar tot el que us voldria dir. Sense vosaltres res hauria sigut possible.

Finalment, voldria agrair-li a Marc haver aparegut a la meua vida i haver sigut un pilar fonamental en aquesta recta final de la tesi. Gràcies per tota la felicitat que m'aportes i per donar-li color als meus dies. Mai hauria imaginat que una partida a la Fallera Calavera em canviaria tant la vida.

Index

Chapter 1

Introduction

1.1 Abbreviations

AB/AD: Abduction/Adduction

ADL: Activity of daily living

ADs: Assistive Devices

ANOVA: Analysis of variance

AROM: Active range of motion

BBT: Box and Block Test

B&E: Biomechanics and Ergonomics

CMC: Carpometacarpal joint

CR: Contact rate

DADL: Domestic activity of daily living

DIP: Distal interphalangeal joint

DoF: Degrees of freedom

EADL: Extradomestic activity of daily living

EGA: Elementary grasp action

EMG: Electromyography

F/E: Flexion/Extension

FMT: Free motion task

FROM: Functional range of motion

ICF: International classification of functioning, disability and health

IP: Interphalangeal

IQ: Interquartile

MCP: Metacarpophalangeal joint

MRI: Magnetic Resonance Image

NR: Neutrality rate

PIP: Proximal interphalangeal joint

PPT: Purdue Pegboard Test

PSM: Physical self-maintenance

P/S: Pronation/Supination

ROM: Range of motion

RULA: Rapid upper limb assessment

SD: Standard deviation

SHFT: Sollerman Hand Function Test

Sig.: Significance level

VMG30: Virtual Motion Glove 30

WHO: World Health Organization

YCB: Yale-CMU-Berkeley

1.2 Aim

The complexity of the human hand, with 25 main degrees of freedom (DoF), provides the required ability to perform activities of daily living (ADLs), being key to ensure personal autonomy and independence. Product manipulation during ADLs has been studied in literature for several purposes (clinical assessment, ergonomics, etc.), and the kinematic parameters used are varied. Some works in literature have presented normative values of several kinematic parameters, such as functional ranges of motion (FROMs) or mean postures, but few works have focused on joint velocity-related parameters during ADLs performance. Furthermore, these studies considered a very limited variety of tasks and products, poorly representative of those used in daily life. Therefore, the aim of this thesis is to contribute to the characterisation of hand kinematics during product manipulation in ADLs, which is formulated as the following main objectives:

- **Hand kinematic characterisation in ADLs by creating and analysing a large dataset of hand kinematic data**. In order to obtain data representative of the real kinematic requirements of ADLs, it was necessary to create a large dataset of hand kinematic data recorded with instrumented gloves on both hands while using a wide variety of products and performing different tasks. In order to make it feasible, as a first step, the database has been limited to tasks and products of two specific fields of ADLs considered key for personal autonomy and independence: feeding and cooking. Then, apart from publishing these data in an open repository to share them with other researchers, tasks recorded were classified according to different features (force type and intended motion) and kinematic parameters were analysed in order to characterise both hands during product manipulation in these two fields of ADLs. Both postural and velocity kinematic parameters were analysed. Among other results, this study contributed to identifying task groups requiring extreme postures or high angular velocities that would be hardly achievable by users with reduced hand function.

- **Analysis of the effect of assistive devices on hand and upper limb kinematics**. Factors such as hand length, aging or impairments that affect upper limb mobility or strength may hinder the performance of tasks or the interaction with specific products. In order to overcome these limitations and to mitigate their effect, assistive devices or universal design solutions are conceived. These products are designed so as to achieve different purposes such as reducing range of motion, reducing the torque to be applied or requiring postures that are more easily achievable. In order to set the design characteristics of these products (e.g.: handle shape, diameter or handle bending), product designers consider how these characteristics affect parameters related with hand biomechanical function while using the products. Nevertheless, hand kinematics of specific hand joints has not been as commonly considered as other parameters such as grasp type, grip strength or contact pressure. For this reason, another of the main objectives of the thesis was to study the effect of specific assistive devices (ADs) design characteristics on hand and upper limb kinematic parameters, and to provide an overview of the effect of the different design characteristics on those parameters. Quantifying certain kinematic parameters of hand joints while manipulating products with different shapes and handles could contribute to minimize mobility requirements or extreme postures, going towards more inclusive designs. It could also contribute to user-centred design approaches, designing more suitable products for specific pathologies, as some postures are difficult to reach by users with pathologies that reduce hand mobility or with impairments that affect manipulation capabilities.

- **Validation of the motion capture system**. Human hand kinematics is complex, and recording all its DoF is challenging, especially when experiments involve product manipulation in the most realistic way. Even though instrumented gloves were chosen as the most suitable motion capture system, researchers from the Biomechanics and Ergonomics Group had some concerns regarding their functioning. For this reason, several experiments were carried out before facing the aims previously mentioned, in order to validate several technical aspects of their use as motion capture system, providing quantifiable information regarding their functioning and technical recommendations to other researchers devoted to hand kinematics.

1.3 Context

The idea originates from the research carried out within the Biomechanics & Ergonomics research group at the Universitat Jaume I (Castelló de la Plana, Spain) with whom I have been collaborating in different periods since 2013. The thesis is framed within one research project funded by the Spanish Ministry (DPI2014-52095-P)

Research group

The research fields of the Biomechanics & Ergonomics (B&E) research group cover biomechanics of the foot and the knee, dental biomechanics, biomechanics of the human hand, ergonomics of hand tools and emotional design. Focusing on the human hand, the group has an extensive background in knowledge, both from an ergonomic and a biomechanical point of view. A better understanding of the human hand can be applied in surgery to improve clinical decision-making, in disability assessment, or in rehabilitation to select the best strategy for the best possible recovering of a pathologic or injured hand. Also, lately the group has started to apply its knowledge to the design and evaluation of anthropomorphic hands. Nevertheless, the work presented in this thesis is focused on contributing to the characterisation of hand kinematics during product manipulation in ADLs by using several quantifiable indicators, as well as in studying the effect of product design in hand kinematics, considering both qualitative and quantitative approaches. The results could be of interest to researchers from fields such as functional assessment, product design or ergonomics.

Research project

This thesis was framed within the research project funded by the Spanish Ministry DPI2014-52095-P (Table 1.3.1) and the Universitat Jaume I predoctoral grant PREDOC 2016/08.

Table 1.3.1. Main data of the DPI2014-52095-P research project.

Reference	DPI2014-52095-P
Title	Kinematic characterisation of the hand aimed to functional assessment of products in activities of daily living
Institution	Spanish Ministry of Economy and Competitiveness and FEDER
Period	2015-2017 (3 years)
Funding	115 000.00 €
Main researchers	Margarita Vergara Monedero Joaquín Luis Sancho Bru
Participants	Verónica Gracia Ibáñez, Néstor J. Jarque Bou, Wendy M. Murray, Alba Roda Sales

This research project started from the prior experience in the field of biomechanics of the hand of the main researchers and their recent collaboration with the ARMS lab of the Rehabilitation Institute of Chicago. The main objectives were to characterise the healthy hand during the development of ADLs with a wide range of products, and creating a database of “normal” values of kinematic parameters for healthy subjects. This information can be useful both to assess the functionality of injured or pathological subjects, in design and development of dexterous prosthetics, for machine learning purposes or for product design.

Research stay

In the fulfilment of the requirements for applying for an international mention in the PhD, I performed a research stay for three months (Sept. 2019 - Dec. 2019) at the Center for Inclusive Design and Innovation (formerly Center for Assistive Technology and Environmental Access) at College of Design of Georgia Institute of Technology (Atlanta, GA, USA), under the supervision of Dr. Jon Sanford.

The Center for Inclusive Design and Innovation is devoted to inclusive innovations in assistive and universally designed technologies, with a goal of addressing the full range of needs for accessibility. They promote user-centred research, products, and services for individuals with disabilities.

This research stay was closely related with the research carried out within this thesis and implied a great opportunity to acquire theoretical knowledge in the field of assistive devices and universal design, as well as in using other motion capture systems. During the stay, apart from attending some lectures in universal and inclusive design, I collaborated with the kinematic analyses performed in the Smart Bathroom project, where the entire posture of an adapted bathroom user was recorded and analysed. The main task was developing a Matlab code for whole body posture calculation from the recordings from Microsoft Kinect cameras. The results obtained from the validation of the camera setup (as well as the main problems faced during the implementation of the system) are being prepared to be submitted to the Annual Meeting of the European Society for Movement Analysis in Adults and Children. Furthermore, the skills acquired in the usage of this motion capture system will be useful for planning next experiments to be carried out in the B&E research group, adding the upper limb posture recording and analysis.

1.4 Structure

The content of the thesis is structured into a State of Art section (Chapter 2), followed by contributions related with the technical validation experiments (Chapter 3), contributions to hand kinematics characterisation during product manipulation in ADLs (Chapter 4), contributions to the effect of ADs design characteristics on hand kinematics (Chapter 5) and a final conclusions section (Chapter 6). Many of the studies presented in the thesis correspond to papers published in international journals or are an extension of communications presented to conferences, as detailed in Table 1.4.1. The works published in international journals have been included in this thesis exactly as they appear in the published versions of the paper. All the co-authors have given their consent to use these publications as part of this doctoral thesis.

The State of Art (**Chapter 2**) presents an overview of the knowledge in two different fields:

(i) Activities of daily living and product manipulation: classification of activities of daily living and main impairments that affect product manipulation capabilities, as well as assistive devices or universal design solutions to mitigate their effects.
(ii) Hand kinematic analysis: hand kinematics, motion capture systems, parameters commonly used in literature to characterise human hand biomechanics, available datasets for their study and an overview of the studies in literature analysing the relationship between products' characteristics and hand kinematics.

Instrumented gloves were chosen as the most suitable motion capture system for the studies to be carried out, according to the revision of the available motion capture systems for hand kinematics recording presented in section 2.2.2. **Chapter 3** contributes to the validation of this motion capture system and highlights important technical aspects to be considered when using it. The outcomes from this part were essential to plan the experiments framed in this thesis, but are also valuable recommendations and advice for other researchers using gloves for studying hand kinematics. This chapter consists of a set of experiments, most of which have been published in international journals or conferences, with different goals:

- Effect on manipulation skills (at different levels of precision) while wearing instrumented gloves.
- Suitability of using gloves that allow the recording of distal interphalangeal joints: observed problems during their use.
- Quantification of the error observed in different conditions (free motion and manipulation) if distal interphalangeal joint angles are estimated from the proximal interphalangeal ones.
- Comparison of two instrumented gloves (equipped vs non-equipped with pressure sensors) regarding their kinematic accuracy and usefulness to distinguish free motion from manipulation during the recordings.

Chapter 4 focuses on contributing to the analysis of hand kinematics during product manipulation in feeding and cooking activities, an important area of ADLs for assuring personal autonomy. A dataset is presented and several kinematic parameters are analysed and presented:

- The KINE-ADL BE-UJI Dataset is presented in section 4.1. This dataset contains a total of 1160 recordings performed by 20 healthy subjects while wearing instrumented gloves in both hands. Anatomical angles while performing feeding and cooking activities using a total of 66 products are provided. This dataset was made publicly available in an open repository (Mendeley Data) and published in the international journal *Scientific Data.*
- In section 4.2, KINE-ADL BE-UJI Dataset is used to characterise both hands kinematics in product manipulation during ADLs (feeding & cooking). Descriptive analyses of postural and velocity-related kinematic parameters were performed, thus providing kinematic requirements depending on task characteristics. Tasks requiring extreme postures, close to the active range of motion, were identified, along with those requiring high extreme velocities or high manipulability, difficult to achieve by people with reduced hand function.

Chapter 5 studies the effects of specific ADs design characteristics on hand and upper limb posture (which was published in the international journal *Applied Ergonomics*) and on hand joints (published in the international journal *PeerJ - Life and Environment*).

Finally, in **Chapter 6**, the main conclusions of the work presented in this thesis are presented, and future work in the research line of the thesis is briefly introduced.

Table 1.4.1. List of chapters and their corresponding publication.

TITLE	PUBLICATION	AUTHORS
CHAPTER 3: USING INSTRUMENTED GLOVES IN HAND KINEMATICS RECORDING WHILE MANIPULATING PRODUCTS		
Effect on manual skills of wearing instrumented gloves during manipulation	Paper published in *Journal of Biomechanics*	A. Roda-Sales, J.L. Sancho-Bru, M. Vergara, V. Gracia-Ibáñez, N. J. Jarque-Bou
Suitability of using instrumented gloves to measure distal interphalangeal joints kinematics	Communication to the *25th Congress of European Society of Biomechanics (2019)*	A. Roda-Sales, J.L. Sancho-Bru, M. Vergara, N. J. Jarque-Bou, V. Gracia-Ibáñez
Relationship between proximal and distal interphalangeal joint angles	Paper in preparation to be submitted to the journal *Human Movement Science*	-
Evaluation of an instrumented glove for its use in the kinematics characterisation during product manipulation	Communication to the *8th World Congress of Biomechanics (2018)*	A. Roda-Sales, M. Vergara J.L. Sancho-Bru, M. Jiménez-Benajes
CHAPTER 4: HAND KINEMATICS IN FEEDING AND COOKING TASKS		
Human hand kinematic data during feeding and cooking tasks	Paper published in *Scientific Data*	A. Roda-Sales, M. Vergara J.L. Sancho-Bru, V. Gracia-Ibáñez, N. J. Jarque-Bou
An analysis of hand kinematics in feeding and cooking tasks	Paper in preparation to be submitted to the journal *Human Movement Science*	-
CHAPTER 5: EFFECT OF ASSISTIVE DEVICES ON HAND KINEMATICS DURING ACTIVITIES OF DAILY LIVING		
Effect of assistive devices on hand and arm posture during activities of daily living	Paper published in *Applied Ergonomics*	A. Roda-Sales, M. Vergara J.L. Sancho-Bru, V. Gracia-Ibáñez, N. J. Jarque-Bou
Effect on hand kinematics when using assistive devices during activities of daily living	Paper published in *PeerJ – Life and Environment*	A. Roda-Sales, M. Vergara J.L. Sancho-Bru, V. Gracia-Ibáñez, N. J. Jarque-Bou

1.5 Other publications and congresses

During the years collaborating with the B&E research group, apart from the publications that are part of this thesis, I contributed to other articles or congress communications, which are presented in Table 1.5.1.

Table 1.5.1: Other publications and congresses that I took part during the development of the thesis.

OTHER PUBLICATIONS AND CONGRESSES	
Paper	Gracia-Ibáñez, V., Sancho-Bru, J.L., Vergara, M, Roda-Sales, A., Jarque-Bou, N.J., Bayarri-Porcar, V. 2020. *Biomechanical function requirements of the wrist. Circumduction versus flexion/abduction range of motion.* Journal of Biomechanics. Vol. 110. pp. 1-7.
Paper	N. J. Jarque-Bou, M. Vergara, J. L. Sancho-Bru, V. Gracia-Ibáñez and A. Roda-Sales, *Hand Kinematics Characterization While Performing Activities of Daily Living Through Kinematics Reduction*, in IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 28, no. 7, pp. 1556-1565, July 2020.
Paper	Gracia-Ibáñez, V., Sancho-Bru, J.L., Vergara, M, Jarque-Bou, N.J., Roda-Sales, A. *Sharing of hand kinematic synergies across subjects in daily living activities*. Sci Rep 10, 6116 (2020).
Paper	Néstor J. Jarque-Bou, Margarita Vergara, Joaquín L. Sancho-Bru, Verónica Gracia-Ibáñez, Alba Roda-Sales. *A calibrated database of kinematics and EMG of the forearm and hand during activities of daily living.* Sci Data 6, 270 (2019).
Paper	Enrique Sanchis-Sales, Joaquín Luis Sancho-Bru, Alba Roda-Sales, Javier Pascual-Huerta. *Variability of the Dynamic Stiffness of Foot Joints: Effect of Gait Speed*. Journal of the American Podiatric Medical Association. July 2019, Vol. 109, No. 4, pp. 291-298.
Paper	Néstor J. Jarque-Bou, Margarita Vergara, Joaquín L. Sancho-Bru, Alba Roda-Sales, Verónica Gracia-Ibáñez. (2018). Identification of forearm skin zones with similar muscle activation patterns during activities of daily living. Journal of Neuroengineeering and Rehabilitation.
Paper	E. Sanchis-Sales, J.L. Sancho-Bru, A. Roda-Sales, J. Pascual-Huerta (2018). *Effect of static foot posture on the dynamic stiffness of foot joints during walking*. Gait & Posture
Paper	Sanchis-Sales E, Sancho-Bru JL, Roda-Sales A, Pascual-Huerta J. *3D characterisation of the dynamics of foot joints of adults during walking*. Gait pattern identification. Comput Methods Biomech Biomed Engin. 2017, Jul;20(9):1015-1030.
Paper	E. Sanchis-Sales, J.L Sancho Bru, A. Roda-Sales, J. Pascual-Huerta (2016). *Kinematics and kinetics analysis of midfoot joints of 30 normal subjects during walking*. Revista Española de Podología, 2016, 27:e6-e12.
Paper	Enrique Sanchis-Sales, Joaquin L. Sancho-Bru, Alba Roda-Sales, Javier Pascual-Huerta (2016). *Dynamic Flexion Stiffness of Foot Joints During Walking.* Journal of the American Podiatric Medical Association, 106, 37-46.

Congress	Verónica Gracia-Ibáñez, Margarita Vergara, Joaquín L. Sancho-Bru, Alba Roda-Sales, Néstor J. Jarque-Bou (2019). *Kinematic synergies of Sollerman Hand Function Test*. 25th Congress of the European Society of Biomechanics. Vienna.
Congress	A. Mestre-Vicente, A. Roda-Sales, V. Gracia-Ibáñez, M. Vergara, J.L. Sancho-Bru. *Validación del uso del sistema Leap Motion para el registro de los ángulos de flexión de la mano.* (2018) VIII Reunión del Capítulo Español de la Sociedad Europea de Biomecánica. Castellón.
Congress	A. Roda-Sales, V. Gracia-Ibáñez, M. Vergara, J.L. Sancho-Bru. *Efecto del uso de guantes instrumentados en la destreza durante la manipulación*. (2018) VIII Reunión del Capítulo Español de la Sociedad Europea de Biomecánica. Castellón.
Congress	V. Gracia-Ibáñez, J.L. Sancho-Bru, M. Vergara, A. Roda-Sales, N. Jarque-Bou. (2018) *Sollerman Hand Function Test: estudio cinemático en base a acciones de vida diaria*. VIII Reunión del Capítulo Español de la Sociedad Europea de Biomecánica. Castellón.
Congress	Verónica Gracia-Ibáñez, Joaquín L. Sancho-Bru, Margarita Vergara, Alba Roda-Sales (2017). *Evaluación funcional de la cinemática de la muñeca mediante el análisis de la circunducción.* XIII Congreso Iberoamericano de Ingeniería Mecánica. Lisboa
Congress	Margarita Vergara, Alba Roda-Sales, Joaquín L. Sancho-Bru, Francisco J. Andrés de la Esperanza, Verónica Gracia-Ibáñez (2017). *Utilización de herramientas de estadística multivariante para clasificar las posturas de la mano.* XIII Congreso Iberoamericano de Ingeniería Mecánica. Lisboa.
Congress	Alba Roda-Sales, Margarita Vergara, Verónica Gracia-Ibáñez, Joaquín L. Sancho-Bru (2017). *Efecto del uso de productos adaptados en la postura del miembro superior durante actividades de la vida diaria.* XIII Congreso Iberoamericano de Ingeniería Mecánica. Lisboa.
Congress	Alba Roda-Sales, Margarita Vergara, Verónica Gracia-Ibáñez, F. J. Andrés, Joaquín L. Sancho-Bru (2017). *Comparison of hand kinematic synergies between both hands on bimanual activities of daily living.* 23rd Congress of the European Society of Biomechanics, Sevilla.
Congress	A. Roda-Sales, M. Vergara, J.L. Sancho-Bru, V. Gracia-Ibáñez (2016). *Quantifying the effect on hand posture when using adapted products for daily líving activities*. ESMAC 25th Annual Meeting, Sevilla. Gait & Posture 49S (2016) 269-270.
Congress	E. Sanchis Sales, J.L. Sancho Bru, P.J. Rodríguez Cervantes, A. Roda Sales, J. Pascual Huerta (2016). *Componentes principales aplicados al estudio de la dinámica del pie supinado y normal durante la marcha*. XXI Congreso Nacional de Ingeniería Mecánica. Elche.
Congress	N. Jarque Bou, J.L. Sancho Bru, M. Vergara, A. Pérez González, A. Roda Sales, S. Mestre Vicent (2016). *Determinación paramétrica de los ejes de rotación de las articulaciones interfalángicas de los dedos.* XXI Congreso Nacional de Ingeniería Mecánica. Elche
Congress	Enrique Sanchis-Sales, Joaquin L. Sancho-Bru, Alba Roda-Sales, Javier Pascual-Huerta. (2016). *Coordination of foot joints during normal gait.* 22nd Congress of the European Society of Biomechanics, Lyon.
Congress	Enrique Sanchis-Sales, Joaquín L. Sancho-Bru, Alba Roda-Sales, Javier Pascual-Huerta (2016). *Caracterización 3D de la dinámica de las articulaciones del pie durante la marcha. Identificación de patrones de la marcha.* Actas de la 1ª Jornada de Biomecánica de la USJ, Zaragoza
Congress	Néstor J Jarque-Bou, Joaquín L Sancho, Margarita Vergara, Antonio Pérez, Alba Roda, Sheyla Mestre (2016). *Determining the position and orientation of rotation axes of interphalangeal joints from skin markers.* 22nd Congress of the European Society of Biomechanics, Lyon

Chapter 2

State of Art

2.1 Activities of daily living and product manipulation

2.1.1 Activities of daily living

Activities of daily living (ADLs) is a term used in healthcare to describe the fundamental skills required to perform self-care daily activities. The ability to perform them is key to achieve a full and autonomous life. In fact, the International Classification of Functioning, Disability and Health (ICF) of the World Health Organization (WHO) [1] established the ability to carry out ADLs as the main factor for classifying the degree of disability, and presented an indexed classification of "Activities and Participation" tasks, subclassified into different fields: learning, general tasks, communication, mobility, self-care, domestic life, interpersonal interactions, major life areas and community/social life.

ADLs can be grossly classified into basic and instrumental ADLs. Basic ADLs refer to the performance of the basic physical needs such as feeding, dressing, personal hygiene or toileting, among others. On the other hand, instrumental ADLs are more complex activities that are not necessary for fundamental functioning but that are required for living independently in a community, such as cleaning and maintaining the house, preparing meals or shopping.

The ability of the human hand to grasp and manipulate is fundamental in order to carry out a great number of ADLs (especially the instrumental ones), as observed in a previous study at the B&E research group [2]: hands are used during a total of 5h 6min (work time excluded) out of 8h 25min per day in average spent performing ADLs (as reported by the American Time Use Survey [3]).

The level of involvement of the hand in a wide range of ADLs was rated in another work of the B&E research group [4] (Tables 2.1.1- 2.1.3). The tasks analysed were those indexed in the section "Activities and participation" of the WHO's ICF classification. The tables present all the chapters and tasks along with their rate of hand use considering the following gradation: (A) there is a direct and unpreventable involvement of the hand, (B) hand is indirectly involved and (C) no hand involvement at all. These tables give an overview of the importance of hand function in ADLs performance and, therefore, in personal independence and life quality. It has to be remarked the high hand use level required for the tasks of the chapters *self-care* (e.g.

drinking or eating) and *household tasks* (e.g. preparing meals or doing housework).

Table 2.1.1: Level of involvement of the hand in "Activities and participation" of WHO's ICF (Part 1).

	LEVEL		
ACTIVITIES AND PARTICIPATION	A	B	C
Chapter 1: Learning and applying knowledge			
Purposeful sensory experiences			
d110 Watching			
d115 Listening			
d120 Other purposeful sensing			
d129 Purposeful sensory experiences, other specified and unspecified			
Basic learning			
d130 Copying			
d135 Rehearsing			
d140 Learning to read			
d145 Learning to write			
d150 Learning to calculate			
d155 Acquiring skills			
d159 Basic learning, other specified and unspecified			
Applying knowledge			
d160 Focusing attention			
d163 Thinking			
d166 Reading			
d170 Writing			
d172 Calculating			
d175 Solving problems			
d177 Making decisions			
d179 Applying knowledge, other specified and unspecified			
d198 Learning and applying knowledge, other specified			
d199 Learning and applying knowledge, unspecified			
Chapter 2: General tasks and demands			
d210 Undertaking a single task			
d220 Undertaking multiple tasks			
d230 Carrying out daily routine			
d240 Handling stress and other psychological demands			
d298 General tasks and demands, other specified			
d299 General tasks and demands, unspecified			
Chapter 3: Communication			
Communicating - receiving			
d310 Communicating with – receiving – spoken messages			
d315 Communicating with – receiving – nonverbal messages			
d320 Communicating with – receiving – formal sign language messages			
d325 Communicating with – receiving – written messages			
d329 Communicating – receiving, other specified and unspecified			
Communicating - producing			
d330 Speaking			
d335 Producing nonverbal messages			
d340 Producing messages in formal sign language			
d345 Writing messages			
d349 Communication – producing, other specified and unspecified			
Conversation and use of communication devices and techniques			
d350 Conversation			
d355 Discussion			
d360 Using communication devices and techniques			
d369 Conversation and use of communication devices and techniques, other specified and unspecified			
d398 Communication, other specified			
d399 Communication, unspecified			

Table 2.1.2: Level of involvement of the hand in "Activities and participation" of WHO's ICF (Part 2).

	LEVEL		
ACTIVITIES AND PARTICIPATION	A	B	C
Chapter 4: Mobility			
Changing and maintaining body position			
d410 Changing basic body position			
d415 Maintaining a body position			
d420 Transferring oneself			
d429 Changing and maintaining body position, other specified and unspecified			
Carrying, moving and handling objects			
d430 Lifting and carrying objects			
d435 Moving objects with lower extremities			
d440 Fine hand use			
d445 Hand and arm use			
d449 Carrying, moving and handling objects, other specified and unspecified			
Walking and moving			
d450 Walking			
d455 Moving around			
d460 Moving around in different locations			
d465 Moving around using equipment			
d469 Walking and moving, other specified and unspecified			
Moving around using transportation			
d470 Using transportation			
d475 Driving			
d480 Riding animals for transportation			
d489 Moving around using transportation, other specified and unspecified			
d498 Mobility, other specified			
d499 Mobility, unspecified			
Chapter 5: Self-care			
d510 Washing oneself			
d520 Caring for body parts			
d530 Toileting			
d540 Dressing			
d550 Eating			
d560 Drinking			
d570 Looking after one's health			
d598 Self-care, other specified			
d599 Self-care, unspecified			
Chapter 6: Domestic life			
Acquisition of necessities			
d610 Acquiring a place to live			
d620 Acquisition of goods and services			
d629 Acquisition of necessities, other specified and unspecified			
Household tasks			
d630 Preparing meals			
d640 Doing housework			
d649 Household tasks, other specified and unspecified			
Caring for household objects and assisting others			
d650 Caring for household objects			
d660 Assisting others			
d669 Caring for household objects and assisting others, other specified and unspecified			
d698 Domestic life, other specified			
d699 Domestic life, unspecified			

Table 2.1.3: Level of involvement of the hand in "Activities and participation" of WHO's ICF (Part 3).

	LEVEL		
ACTIVITIES AND PARTICIPATION	A	B	C
Chapter 7: Interpersonal interactions and relationships			
General interpersonal interactions			
d710 Base interpersonal interactions			
d770 Intimate relationships (include sexual relationships)			
d729 General interpersonal interactions, other specified and unspecified			
Particular interpersonal relationships			
d730 Relating with strangers			
d740 Formal relationships			
d750 Informal social relationships			
d760 Family relationships			
d770 Intimate relationships			
d779 Particular interpersonal relationships, other specified and unspecified			
d798 Interpersonal interactions and relationships, other specified			
d799 Interpersonal interactions and relationships, unspecified			
Chapter 8: Major life areas			
Education			
d810 Informal education			
d815 Preschool education			
d820 School education			
d825 Vocational training			
d830 Higher education			
d839 Education, other specified and unspecified			
Work and employment			
d840 Apprenticeship (work preparation)			
d845 Acquiring, keeping and terminating a job			
d850 Remunerative employment			
d855 Non-remunerative employment			
d859 Work and employment, other specified and unspecified			
Economic life			
d860 Basic economic transactions			
d865 Complex economic transactions			
d870 Economic self-sufficiency			
d879 Economic life, other specified and unspecified			
d898 Major life areas, other specified			
d899 Major life areas, unspecified			
Chapter 9: Community, social and civic life			
d910 Community life			
d920 Recreation and leisure			
d930 Religion and spirituality			
d940 Human rights			
d950 Political life and citizenship			
d998 Community, social and civic life, other specified			
d999 Community, social and civic life, unspecified			

Apart from WHO's ICF and the classification of ADLs into basic and instrumental, other levels of classification have been proposed in literature, such as the three-level one proposed in [5] (Table 2.1.4): domestic activities of daily living (DADLs), extradomestic activities of daily living (EADLs) and physical self-maintenance (PSM) activities. The category of DADLs contains tasks spanning those regularly performed in human living environments, while the EADLs contains activities mainly performed outside home. PSM contain those tasks most important of need for a full and independent life.

According to Table 2.1.3, DADLs and PSM activities require a higher level of involvement of the hand.

Table 2.1.4: Classification of ADLs proposed in [5].

TASK CODE	TASK DESCRIPTION
DADL1	Food preparation
DADL2	Housekeeping
DADL3	Laundry
DADL4	Telephone/computer/technology use
DADL5	Office tasks/writing
DADL6	Hobby/sport
EADL1	Transportation/driving
EADL2	Shopping
EADL3	Employment-related tasks/tool use
PSM1	Feeding/medicating
PSM2	Toileting
PSM3	Bathing
PSM4	Dressing
PSM5	Grooming
PSM6	Ambulation/transfer

2.1.2 Manipulation in ADLs

Performance of tasks using the hands are often characterised by distinguishing three different phases: reaching, grasping/manipulation and release (Figure 2.1.1). In the reaching phase (known also as pregrasp phase in robotics) the hand follows a trajectory in the space in order to approach the object [6], [7] (hand transportation). At the same time, temporal changes in finger and thumb joint parameters take place, so as to configurate their posture in order to perform the intended grasp [6], [7] (hand preshape). While the hand transportation is influenced by the distance of the object from the hand [6], [8], the hand preshape depends on the shape of the object to be grasped [6], [8], [9]. Then, when the hand contacts the object, the grasping/manipulation phase starts. Firstly, a static grasp is usually performed in order to hold the object. In basic ADLs this grasp is usually maintained throughout the task development, and the required movement of the object is achieved by moving more proximal upper limb joints (shoulder, elbow and wrist), such as in combing the hair. Instrumental ADLs usually require a within hand manipulation of the object, such as writing a text message using the mobile phone. Manipulation is the process required to relocate the object within the hand in order to perform the task (but assuring dynamic stability of the object), and it requires that fingers and thumb change their posture to vary the contact points with the object, as well as the contact pressure applied. The grasps during manipulation are chosen by the operator on the basis of the mobility and dexterity required to manipulate the object. Therefore, the grasping/manipulation phase can be as complex as simultaneously transporting (by hand transportation) and precision handling [10], [11] the object, changing its pose with respect to both the environment and the palm. Finally, once the manipulation or grasp required for the task finishes, the object has to be released. The release phase starts when hand configures the posture to release the object. During release the hand opens, and contact decreases until being null. Then, once the object is released, the hand experiences again temporal changes in joint angles until it comes back to a neutral or natural position, at the same time following a trajectory in space (hand transportation), moving toward a resting position or starting another task.

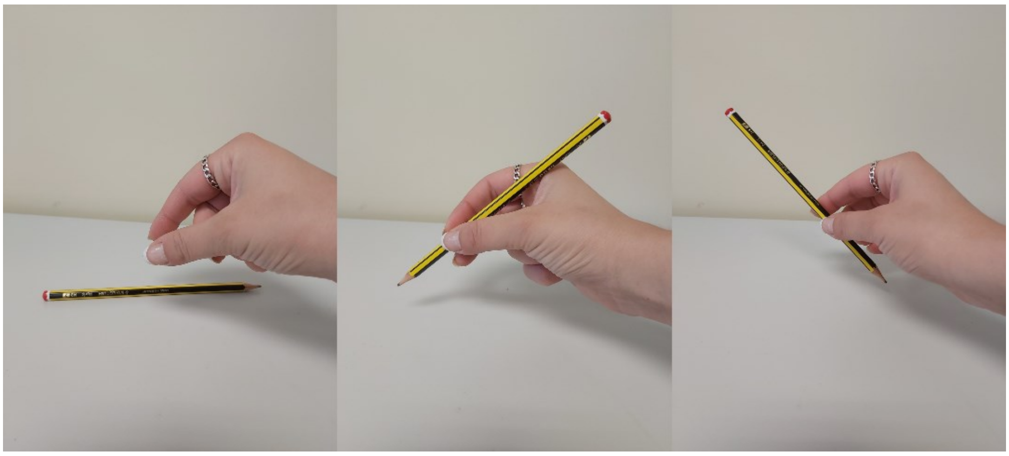


Figure 2.1.1: Example of reaching (left), grasping/manipulation (centre) and release (right) phases.

During the reaching and release phases the hand moves freely, there is no contact with any object, so that the hand movement is commonly known as *free motion*. Nevertheless, during the grasping/manipulation phase the hand contacts the object(s), which affects the hand kinematic behaviour (e.g., passive extensions of joints may appear during grasping (Figure 2.1.2), in contrast to free motion). Section 3.4 presents a study where distal interphalangeal joints' kinematic behaviour is studied and compared both in free motion and grasping/manipulation conditions, evidencing different kinematic patterns. It is therefore important to distinguish the different manipulation phases when studying hand kinematics during ADLs. This distinction can be performed manually by visual inspection, or it can be automated by using pressure sensors. Section 3.5 presents an experiment that compares (among other aspects) the accuracy of distinguishing grasping/manipulation from free motion using visual analysis or an instrumented glove equipped with pressure sensors.

Figure 2.1.2: Passive extension of index distal interphalangeal joint while holding a key.

Another useful classification for the study of hand kinematics during manipulation is distinguishing the type of movement performed with the object during the grasping/manipulation phase. Some works [12] used the parameter *flow*, proposed in the Laban Effort and Shape analysis notation [13]. In this work [12] they annotated the motion as *free* (when the moving direction of the gesture was very casual, such as throwing a ball (Figure 2.1.3A)), *bound* (when the movement was very stiff or controlled, such as putting a key into a keyhole (Figure 2.1.3B)) and *half-bound* (when the movement was controlled along one or more axes of movement but free in the rest, such as dragging toilet paper (Figure 2.1.3C)).

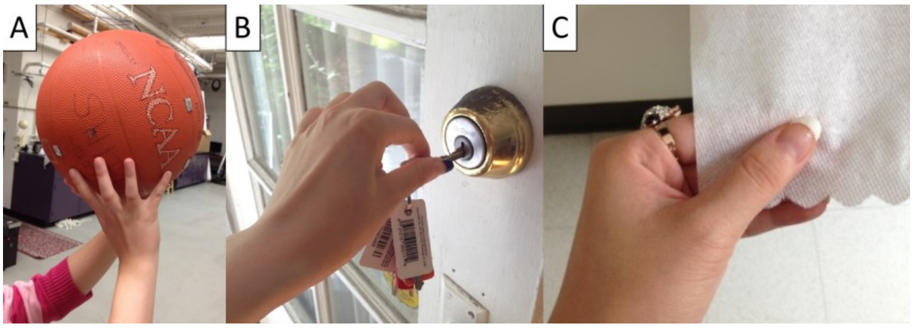


Figure 2.1.3: Examples of tasks where the flow parameter was considered free (A), bound (B) and half-bound (C).

Reaching and grasping have been widely studied in robotics and prosthetics. The main concern in robotics is selecting a proper approach to the object that allows a robust grasp. Manipulation of the object is based mainly on relocating the object with the proximal arm joints, while maintaining the grasp stability. Within hand manipulation of the object has been poorly studied. Human hand behaviour is complex, and several aspects such as sensorial information (visual, tactile, etc.), motor abilities or dexterity/skills, muscular complex or neurologic factors take part in grasping and manipulation. For this reason, prosthetic hands allow performing tasks requiring gross manipulation dexterity (as grasping objects with most common grasp types) but experience difficulties when performing tasks requiring fine manipulation dexterity, as there is still a long way to achieve the manipulation capabilities and control of human hand.

2.1.3 Factors hindering manipulation and solutions

The ability to grasp and manipulate is key to achieve a full autonomous life, as observed in the previous section. Nevertheless, there are some factors such as aging, pathologies, hand injuries or disabilities that affect hand function and, therefore, patient's life quality. To a lesser extent, other factors such as hand length (extremely large or small hands) or laterality also affect hand function when product manipulation is required, as products have been commonly designed for healthy right-handed subjects with average hand length.

Inevitably, hand function decreases with age owing to a deterioration of structures such as bones, joints, muscles and tendons, among others, affecting aspects such as hand mobility, grip strength, grasp stability or dexterity. These age-related changes are often accompanied by common pathological conditions in elderly population, such as osteoporosis, osteoarthritis, rheumatic arthritis or Parkinson's disease [14].

Furthermore, other hand and wrist pathologies such as hand ganglion cysts, deformities (Figure 2.1.4) (e.g. swan neck deformity, Boutonnière deformity or Dupuytren's contracture), nerve related pathologies (as tunnel carpal syndrome), trigger finger or infections affect hand and wrist function. Moreover, other pathologies not directly related with hand can affect its functionality, such as stroke, muscle atrophy and dystonia or sclerosis. Apart from this, hand injuries (as sprains, fractures, dislocations, soft tissue/tendon injuries or amputations) and some disabilities reduce significantly hand functionality.

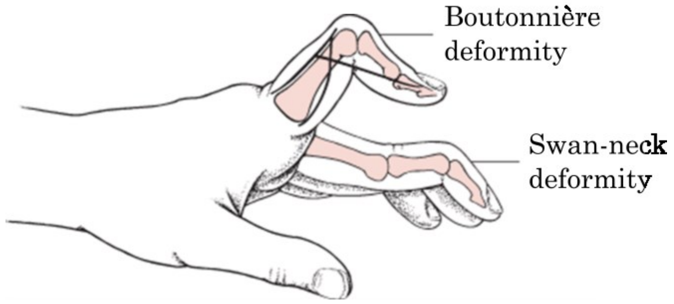


Figure 2.1.4: Postural effects of swan-neck and Boutonnière deformities. Figure extracted from MSD Manuals [15].

For this reason, in order to ensure that products can be used by the majority of people regardless their age, size, ability or disability, it is important to consider the main principles of Universal Design. Those principles consider aspects such as use equitability, flexibility, simplicity and intuitiveness, perception of information, tolerance for error, low physical effort and appropriate size.

Even though sometimes the effect produced by some pathologies cannot be compensated using products designed following Universal Design guidelines, and it requires applying additional solutions. An alternative commonly prescribed to mitigate the effect of these pathologies or impairments on patients' ability to perform ADLs are assistive devices. Grasping and manipulation assistive devices are a good choice both for elderly population and patients with upper limb pathologies or certain disabilities. These devices present special design features intended to ease the development of ADLs by reducing the manipulation precision required (e.g. thickened or bended cutlery handles) (Figure 2.1.5) or the torque applied (e.g. adding an extra handle to a faucet) (Figure 2.1.6), among others. For this reason, as not all the assistive devices help to mitigate the same limitations, the prescription process is key in order to select the most appropriate one.

Figure 2.1.5: Normal spoon and spoons with thickened and/or bended handle.

Figure 2.1.6: Additional handle to a faucet.

Apart from this, prosthetics field has experienced a rise during last decade. Replicating human hand behaviour is challenging in the field of anthropomorphic hand prostheses, as well as in robotic manipulation. Several hand prostheses types are commercially available nowadays, from passive prosthesis (which do not have active movement) to electrically powered ones (which are powered with batteries and controlled from the electrical signal of the remaining limb) (Figure 2.1.7). For the development and improvement of this electrically controlled prosthesis, as well as for the development of anthropomorphic robotic systems, it is key to characterise human hand behaviour through experimental data collected over humans, in order to achieve the most human-like behaviour. Studying parameters such as synergies or grasp types is a common practice in the field. Thus, here relies another important reason for collecting and studying human hand kinematics during ADLs performance, as ADLs are majority of tasks performed by hand prostheses users.

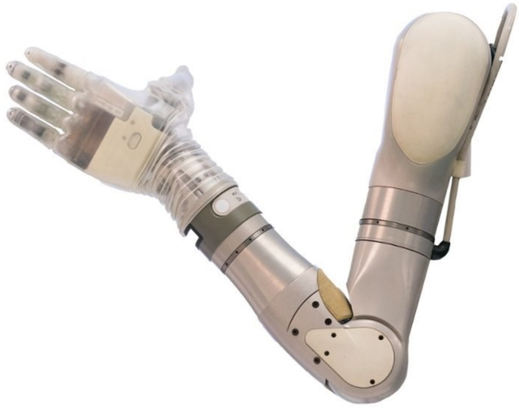


Figure 2.1.7: Electrically powered upper limb prosthesis from Arm Dynamics (CA, USA).

2.2 Hand kinematic analysis in ADLs and product manipulation

2.2.1 Hand kinematics

The human hand is a complex system, with 25 main degrees of freedom. Apart from the well-known division of hand structure into palm, thumb, index finger, middle finger, ring finger and little finger, its bone structure can be divided into three main parts: phalanges, metacarpus and carpus.

The phalanges are those bones composing the digits and can be divided into five groups, depending on the digit to which they correspond (from thumb (digit 1) to little (digit 5)) (Figure 2.2.1). Each of these groups is therefore composed by a proximal, medial and distal phalanx (except for the thumb, which only has two phalanges).

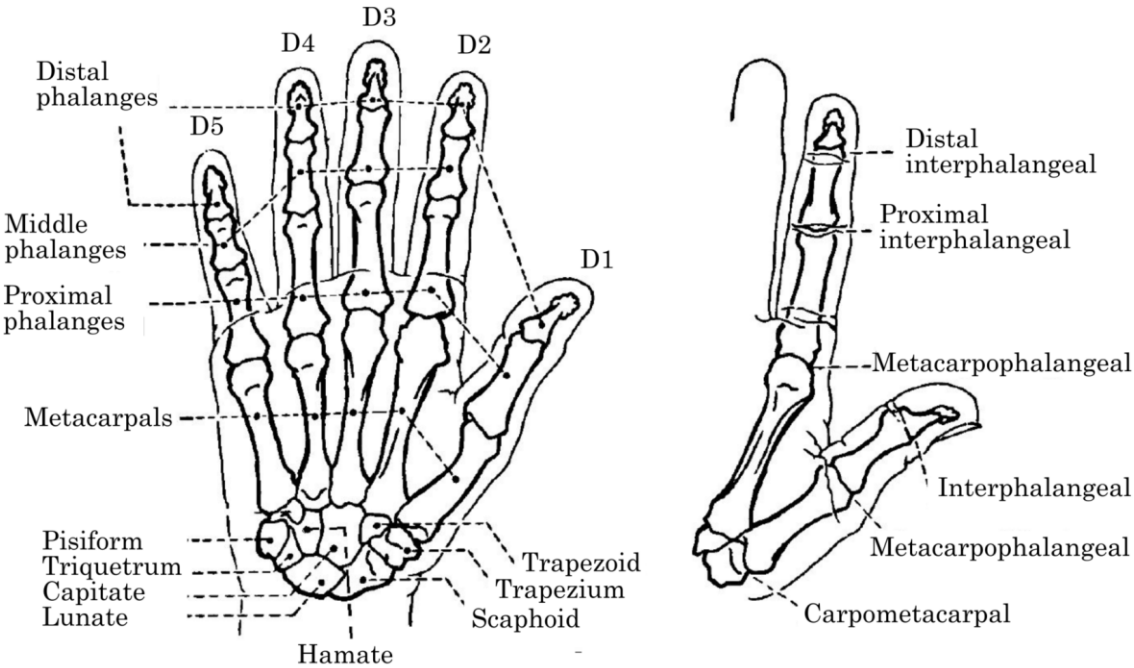


Figure 2.2.1: Hand bones and joints. Digits: thumb (D1), index (D2), middle (D3), ring (D4) and little (D5). Figure adapted from [16].

The joints interconnecting the phalanges are the interphalangeal joints. The distal interphalangeal joints are the ones that connect distal phalanges with middle phalanges, and the ones connecting middle and proximal phalanges are the proximal interphalangeal joints (except for the thumb, which only has an interphalangeal joint). Interphalangeal joints are trochlear joints (grooved structure) (Figure 2.2.2), allowing therefore mainly a single DoF, which is, in this case, flexion/extension (F/E).

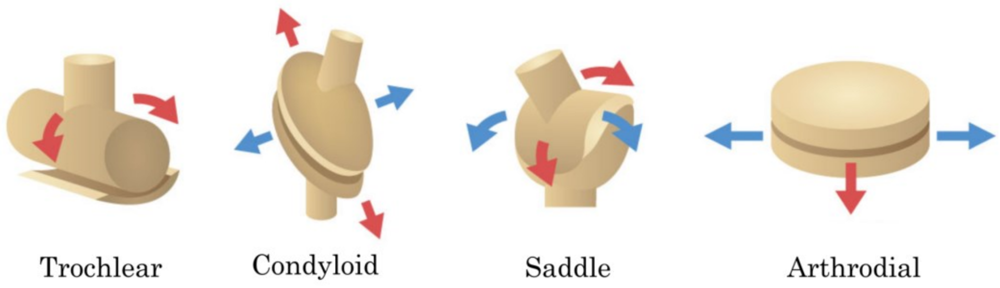


Figure 2.2.2: Trochlear, condyloid, saddle and arthrodial joint types. Figure adapted from [17].

The joints interconnecting each proximal phalanx with the metacarpus bones are the metacarpophalangeal joints. These are condyloid joints (the oval-shaped condyle of the metacarpal bone fits into the elliptical cavity of the proximal phalange bone) (Figure 2.2.2), therefore allowing two main DoFs: F/E and abduction/adduction (AB/AD) (Figure 2.2.3). Metacarpophalangeal joints, along with the interphalangeal ones, are the ones with greatest mobility in the hand [18].

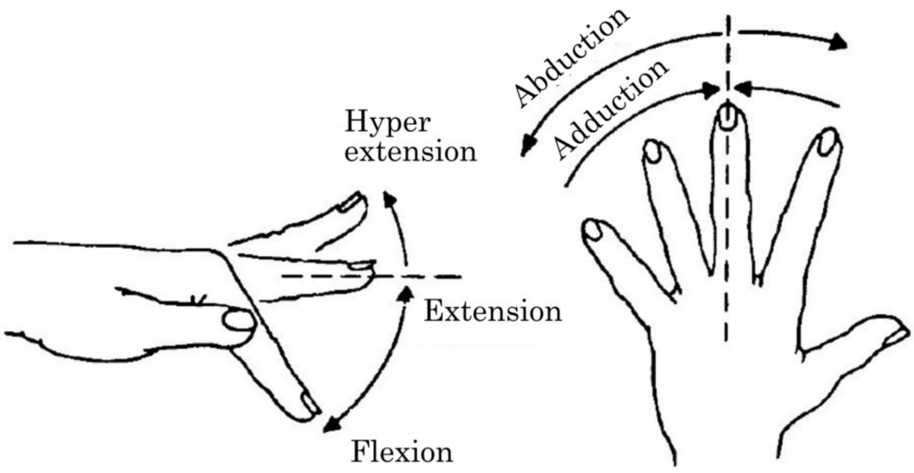


Figure 2.2.3: Movements performed by the fingers. Figure adapted from [16].

The metacarpus is composed by the bones of the palm and, again, bones are numbered from thumb (digit 1) to little (digit 5). The joints that connect metacarpus with carpus are the carpometacarpal ones. The carpometacarpal joint with greatest mobility is the thumb one, which is a saddle joint (Figure 2.2.2), allowing two main DoFs (F/E and AB/AD). This mobility, combined with the mobility of thumb metacarpophalangeal and interphalangeal joints, allows the movement of opposition (touching the little finger base with thumb's tip) (Figure 2.2.4). Nevertheless, the fingers' carpometacarpal joints are arthrodial joints (Figure 2.2.2), which allow gliding movement in the plane of the articular surface (two main DoFs). Their mobility is reduced, but increases gradually from index to little finger.

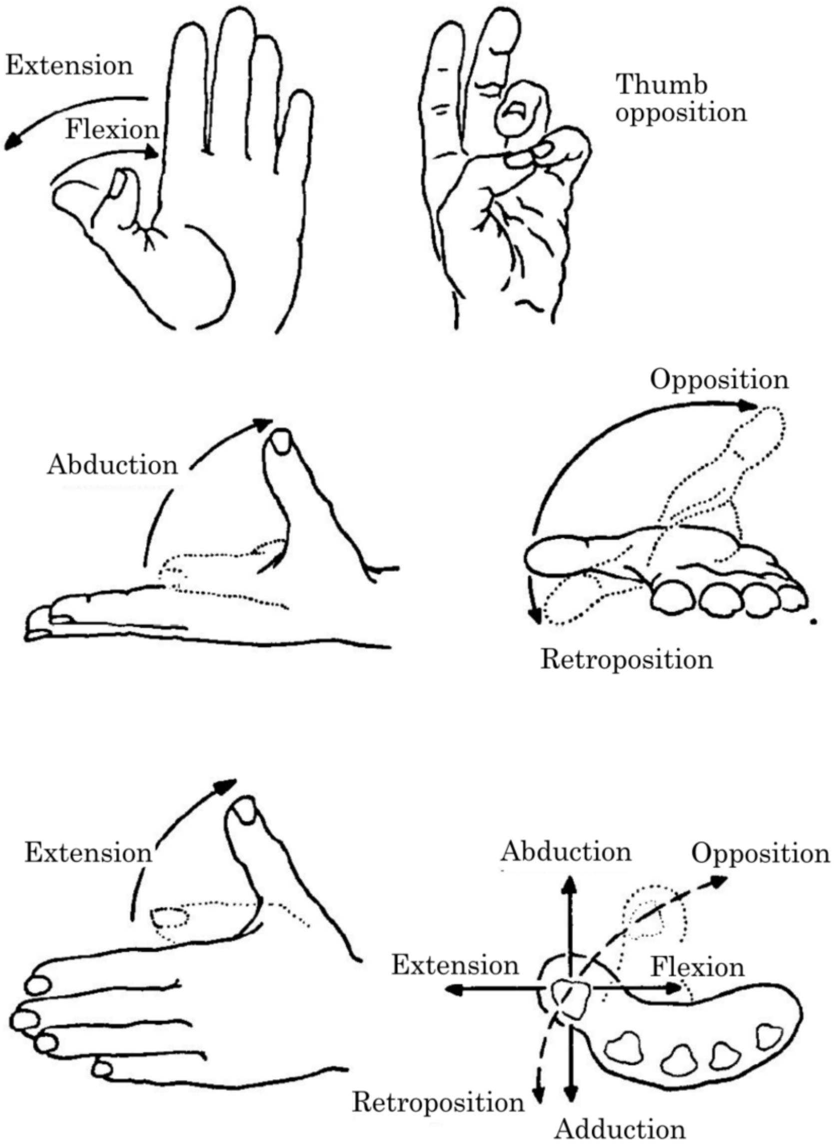


Figure 2.2.4: Movements performed by the thumb. Figure adapted from [16].

The carpus is composed by the bones between the metacarpus and the wrist: scaphoid, lunate, triquetrum, pisiform, trapezium, trapezoid, capitate and hamate. All these bones are connected by the intercarpal joints, which are also arthrodial joints allowing gliding movement in the plane of the articular surface (nevertheless, their relative movement is very low). Finally, scaphoid, lunate and triquetrum bones are connected to the forearm bones (radius and ulna) by the wrist, which is a condyloid joint, allowing two main DoFs: F/E and AB/AD (commonly known as radial/ulnar deviations) (Figure 2.2.5).

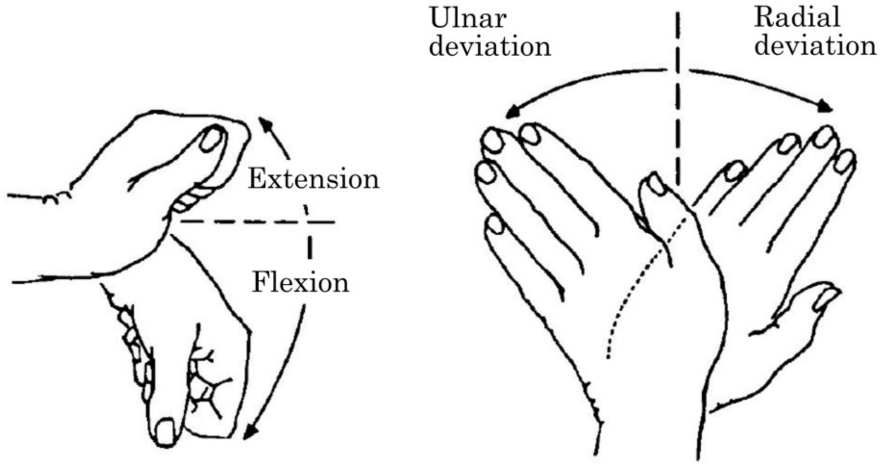


Figure 2.2.5: Movements performed by the wrist. Figure adapted from [16].

The commonly used terminology to identify the relative position of the parts of the hand regarding the three spatial directions is detailed in Figure 2.2.6.

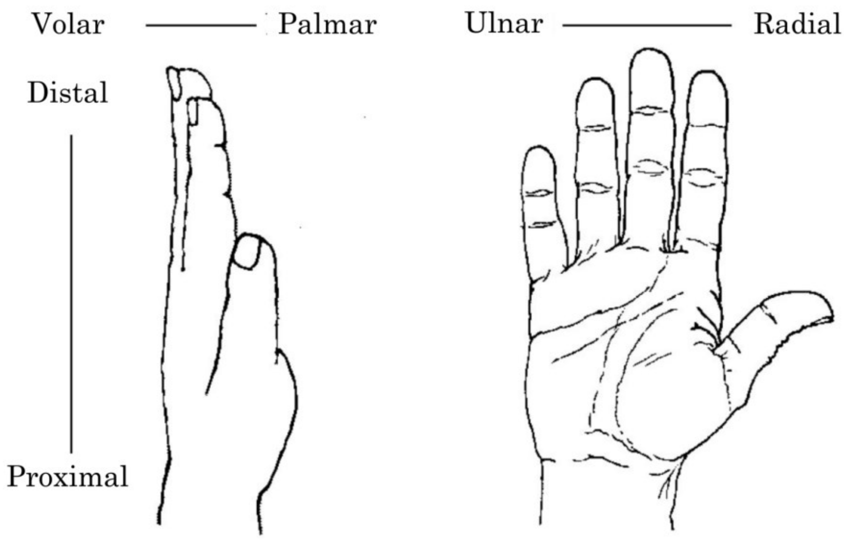


Figure 2.2.6: Terminology to identify the relative position of hand parts. Figure adapted from [16].

2.2.2 Motion capture systems

Motion capture systems record the instant position of an object in space with time, providing a continuous recording of its position and, therefore, allowing kinematic study of body segments. These systems have experienced an evolution in the last decades, with sensor technologies. In the first motion capture analyses the most common technique used was photogrammetry (Figure 2.2.7). This technique consisted in obtaining the dimensions, position and orientation of a physical object and its environment by means of video recordings and performing kinematic calculations over each photogram. Nevertheless, in order to automatically acquire data, systems based in several technologies were developed.

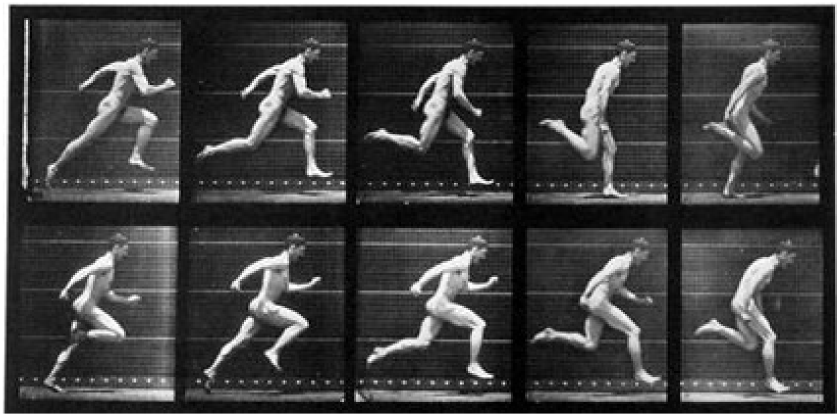


Figure 2.2.7: Photograms extracted from a video recording to perform kinematic calculations.

Electromagnetic systems

Electromagnetic systems consist of an electromagnetic field transmitter and several receivers, which are placed in the body segments to study. The transmitter generates a magnetic field, which is detected by the sensors with different intensity depending on their position in space. Some devices such as Polhemus Fastrak (Polhemus, VT, USA) (Figure 2.2.8) are commonly used in upper limb motion capture, and specific reduced micro sensors using this technology have been developed during recent years, which allow measuring hand joint motion (Figure 2.2.9) with a resolution of 0.001mm at 30cm range and 0.0003º in orientation (according to manufacturer). Nevertheless, these systems present data interferences when using them near to ferromagnetic materials, as the magnetic field generated is altered by them, limiting their use in different environments.

Figure 2.2.8: Electromagnetic motion capture system Fastrak Polhemus.

Figure 2.2.9: Micro sensors developed by Polhemus.

Inertial systems

Inertial measurement units (Figure 2.2.10) are a promising alternative for the study of upper limb kinematics. They are usually composed of accelerometers, magnetometers and inclinometers, allowing the measurement of posture and velocity of a body segment. These systems are a good alternative when performing gait or upper limb posture analyses, and different algorithms have been developed in order to increase their precision by compensating their kinematic measurement error (especially when recording motion with high acceleration or when recording in environments with ferromagnetic materials, which cause signal interferences). Systems such as VN100 by VectorNav Technologies (Figure 2.2.10) (acquired by the B&E research group) present a resolution of 0.001° in orientation (according to manufacturer). Nevertheless, owing to the size of the commercially available sensors, the only joint that could be recorded in hand kinematics studies would be the wrist (Figure 2.2.11).

Figure 2.2.10: Inertial measurement unit (IMU) VN100 by VectorNav Technologies.

Figure 2.2.11: IMUs located to measure the wrist.

Optical systems

These systems make use of the recordings from several cameras in order to obtain position and orientation of an object in the space by triangulation. Optical systems, especially videogrammetric systems with reflective markers such as Vicon (Vicon Motion Systems, UK) (Figure 2.2.12), allow recordings with positioning error lower than 2mm [19]. Several studies using it to measure hand and upper limb have been carried out in B&E research group, and a videogrammetric method to measure the movement of the hand was developed and validated [20]. Figure 2.2.13 shows the position of the 29 reflective markers used in this videogrammetric technique to measure 25 DoF. Nevertheless, optoelectronic systems present problems of occlusion, especially when performing some movements or manipulating objects (e.g. when taking an object from a box/bag, putting a shirt on, taking something from a cabinet or drying the hands with a towel).

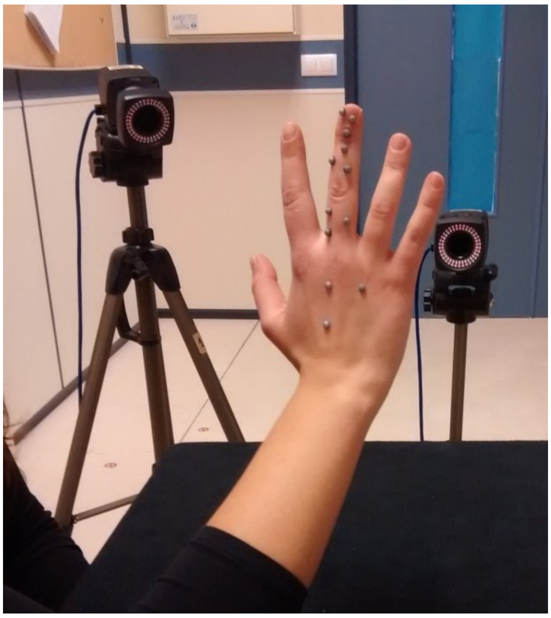


Figure 2.2.12: Setup for hand kinematics recording using a Vicon optical system.

Figure 2.2.13: Location of markers in the videogrammetric method presented in [20].

Electromechanical systems

Electromechanical systems record motion by means of strain gauges attached to the joints. These gauges are metallic layers that vary their electrical resistance depending on their bending, allowing the measure of the anatomical angle. Electromechanical systems such as electrogoniometers are widely used in biomechanics for applications such as gait analysis [21] or upper limb analysis [22] (Figure 2.2.14), among others. Electrogoniometers such as the twin-axis goniometers by Biometrics Ltd. (Figure 2.2.14) present a resolution of 0.1°.

Figure 2.2.14: Electrogoniometer by Biometrics Ltd. (UK) located in the wrist.

They allow recording in environments with ferromagnetic materials without losing precision (contrarily to the electromagnetic systems) and do not present occlusion problems as the optoelectronic ones. These systems allow measuring directly the joint angle between two consecutive segments, but they do not allow obtaining the position in space of the segments, as other motion capture systems. This sensor technology has been also implemented in instrumented gloves, which makes it handy for hand kinematics analysis.

For all these mentioned reasons, the instrumented gloves were chosen to be the most suitable motion capture system for the purpose of the experiments developed in this thesis. Specifically, the CyberGlove instrumented glove (Figure 2.2.15) has been used. These instrumented gloves are composed of extensiometric gauges embedded into an elastic glove. The number of gauges dictate the DoFs the gloves can measure (the model with 22 gauges allows measurement of distal interphalangeal joints, while the 18 DoFs one does not). The extensiometric gauges are located on the specific joints to measure, and the signal provided by each gauge (in mV) varies depending on its flexion, with a mean error of 4.45° when calibrated [23].

Figure 2.2.15: CyberGlove instrumented glove.

2.2.3 Parameters and methods used for kinematics characterisation

Several methods have been used in literature in order to characterise hand and upper limb kinematics during grasping and manipulation. These methods can be grossly classified into qualitative and quantitative methods. While the first ones are more focused on classifying postures and tasks into specified taxonomies, the second ones are numerical indicators that allow quantifying specific kinematic or kinetic aspects.

Qualitative kinematic parameters and methods

Table 2.2.1 presents some of the qualitative parameters and methods commonly used to assess kinematics in biomechanics and ergonomics assessment. Posture of the entire upper limb can be assessed by means of visual analysis methods such as the widely used Rapid Upper Limb Assessment [24]. Hand posture is commonly studied by means of using grasp taxonomies [25]–[28], being based in the combination of several variables such as the task type performed (resting, grasping, etc.), the number of fingers involved when interacting with an object, the specific fingers involved or fingers' posture during the interaction.

The most known taxonomy distinguishing grasp types is the Cutkosky's one, which was originally developed for robotics [29] (Figure 2.2.16). It firstly distinguishes between power and precision grasps, and then classifies them depending on the object's shape and then on hand posture. This classification served as a reference to develop other grasp taxonomies commonly used nowadays in the field of hand kinematic analysis [27]. An interesting adaptation of Cutkosky's taxonomy was presented in [5] (Figure 2.2.17), by taking into account certain aspects such as the presence of contact or the presence of motion during task performance, among others (see Table 2.2.2).

Nevertheless, hand kinematics have been also assessed using other taxonomies focused in the task performed [30], [31], or in the object grasped

[29]. In this regard, the taxonomy presented in [12] is specially interesting, which proposed a format for augmenting grasp taxonomies that included features such as force type (Table 2.2.3) or products' characteristics (weight, material, shape, size and roughness). Even though these features may be very useful to characterise simple grasping and manipulation tasks, identifying force types during ADLs is difficult, as some of them can be applied simultaneously, owing to the complexity of real ADLs.

Table 2.2.1: Qualitative parameters and methods commonly used to assess posture. Examples of works that use them in column "REF.". Taxonomy abbreviated as "Tax.".

REF.	PARAMETER/ METHOD	ADDITIONAL INFO	CLASSIFICATION
[25]	Hand posture	-	Tax. based in task performed and number of fingers involved when interacting with an object. Tasks considered: ▪ Resting ▪ Palm touch ▪ Tip touch ▪ Palm wrap ▪ Finger wrap ▪ Finger Pinch Other entire body parameters
[26]	Hand posture	Based in Hwang (2010) and Wang (2012).	Tax. based in task performed, number of fingers involved and specific fingers involved when interacting with an object. Tasks considered: ▪ Resting ▪ Grasping ▪ Pinching ▪ Touching ▪ Specific abbreviations with the number of fingers involved, first letter of the task and first letter of each finger involved (e.g.: 5G TIMRL for 5 finger grasp)
[24]	RULA	-	Method assessing the following items using a scoring table: ▪ Arm and wrist: upper arm, lower arm and wrist position; wrist twist; muscle use; force/load. ▪ Neck, trunk and leg: Neck, trunk and leg position; muscle use; force/load.
[27]	GRASP tax.	Synthesis of 22 grasp tax. (Kapandji, Cutkosky, etc.)	Taxonomy based in fingers' posture when interacting with the object. 33 grasp types taxonomy (17 standard grasps)
[31]	Microinterac-tions tax.	-	Defines microinteraction or microgestures as those tasks that allow to execute a secondary task without interrupting the manual primary task. 21 microinteraction tax.
[30]	Tax. of functional upper extremity motion	Composed of basic primitives	Characterises those primitives as upper extremity functional motions occurring during ADLs. Primitives considered: reach, reposition, transport, stabilize and idle.

[28]	Grasp taxonomy	-	Tax. based in fingers' posture when interacting with the object. 48 grasp types tax.
[2]	Grasp tax.	Based on Edwards tax. [28]	Tax.based in fingers' posture when interacting with the object. 9 grasp types tax.
[29]	Grasp tax. focused in the object grasped	-	Grasp tax. emphasising mainly in product shape (geometry and size), classifying it at different levels.
[5]	Task tax.	-	Task tax. considering aspects such as the presence of contact or the presence of motion during task performance, among others.
[12]	Grasp tax.	-	Grasp tax. to widen the existing grasp taxonomies, taking into account force type or products' characteristics.

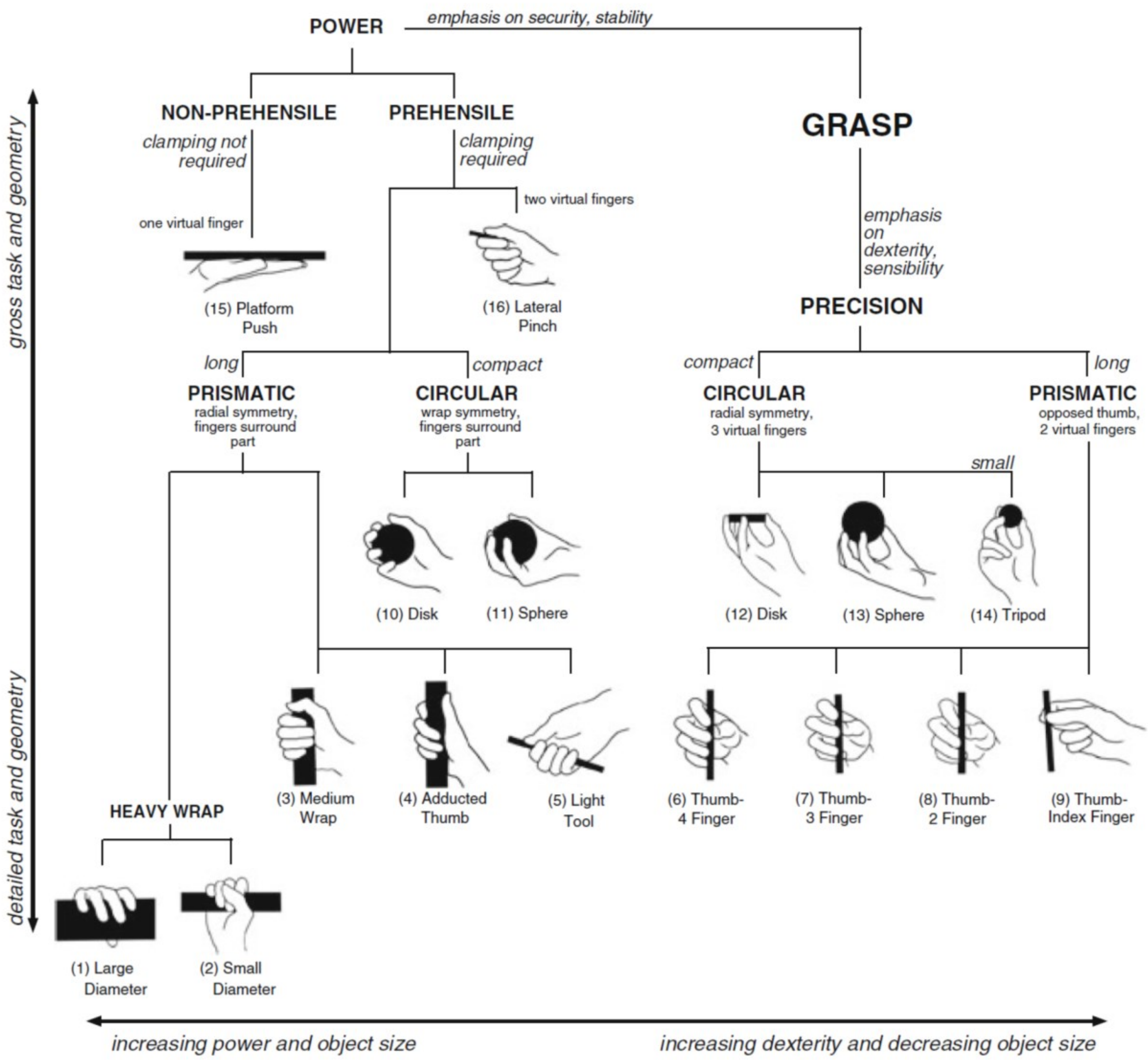


Figure 2.2.16: Adaptation in [5] *of Cutkosky grasp taxonomy*

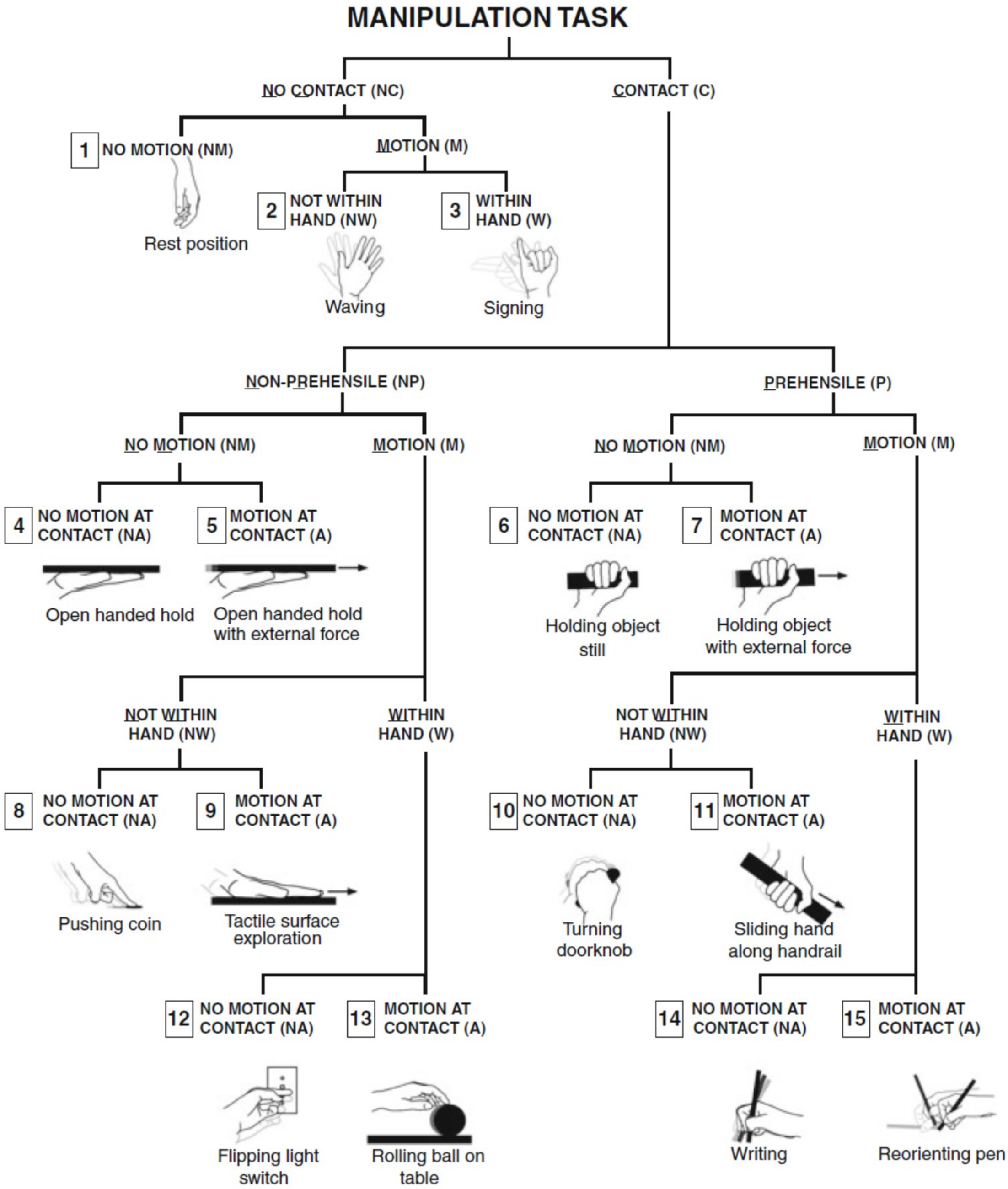


Figure 2.2.17. Manipulation tasks classification proposed by Dollar in [5].

Table 2.2.2. Concepts assessed in [5] *when classifying manipulation tasks.*

CONCEPT	DESCRIPTION
Contact	Hand is touching an external object or the environment.
Prehensile	Action of hand on object must be described with more than one virtual finger.
Motion	Any part of the hand moves relative to body fixed frame.
Within hand	Points on the hand are moving relative to the hand base frame.
Motion at contact	Object reference frame moves relative to contact point frame(s).

Table 2.2.3: Force type definitions considered in [12].

FORCE TYPE	DEFINITION
Break off	Remove a part of an object
Extend	Apply outward forces from within the object
Grab	Hold or secure without opposing gravity
Hold	Grasp object in a way that resists gravity
Lever	Pivot one end of an object around a fixed end
Lift	Apply upward force greater than gravity
Place	Put something in a specified position
Press	Exert force in a direction away from the shoulder
Pull	Exert force in a direction towards the shoulder
Punch	Press or push with a short, quick movement
Put in	Insert one object into another
Roll	Cause rotation without prehension
Rub/stroke	Move back and forth while pressing
Scratch	Rub with something sharp or rough (with the hand directly or a tool)
Squeeze	Apply compressive force around object greater than needed to hold object
Take out	Remove one object from another
Throw	Propel an object through the air
Turn	Flip or rifle through pages
Twist	Cause rotation with prehension
Swing	Move with a smooth, curving motion like hand waving or arm swinging

All these qualitative methods presented can be easily implemented by any research group, as no instrumentation apart from a video camera is required, although they can be highly time consuming. In this thesis, hand posture will be qualitatively analysed for a general understanding of the kinematics using the grasp taxonomy proposed by the B&E research group in a previous study [2], which is based on Edwards' one [28], but considering only nine types of grasp (being one of them a non-prehensile one) (Table 2.2.4 and Figure 2.2.18). This taxonomy was selected owing to its simplicity, as the ones based on Cutkosky's taxonomy are hardly applicable for visual analysis of ADLs performed in a natural way at common speed, and using products representative of the ones used during ADLs. Regarding upper limb analysis, the RULA method [24] will be used for the qualitative analysis of the entire upper limb posture assessment.

Table 2.2.4: Grasp taxonomy used in [2].

GRASP	DESCRIPTION
Cylindrical grasp (Cyl)	The palm is involved. The thumb is in direct opposition to the fingers (in abduction or neutral).
Oblique palmar grasp (Obl)	Variation of the Cylindrical grasp. The palm is involved, but the thumb is adducted.
Hook grasp (Hook)	Palm and thumb are not involved. The object's weight is borne by finger.
Lumbrical grasp (Lum)	Thumb and proximal part of the fingers are involved, but the palm is not involved
Intermediate power-precision grasp (IntPP)	The palm is somewhat involved but both the thumb and index stabilize the grasp.
Pinch grasp (Pinch) or pad to pad pinch (PpPinch)	Thumb and fingertips (one or more) are used.
Lateral pinch (LatP)	The lateral part ofthe fingers (one or more) are used, and usually the thumb as well.
Special pinch (SpP)	The thumb, lateral part of some finger and the fingertips of another/others are involved.
Non-prehensile grasp (NonP)	Objects are manipulated without grasping them.

Figure 2.2.18: Grasp taxonomy proposed in [2]. *Grasps labelled as in Table 2.2.4.*

Quantitative kinematic parameters

Table 2.2.5 presents an overview of the commonest quantitative parameters used to assess hand and upper limb posture. Quantitative kinematic parameters are varied, and their applicability will depend on the nature of the data collected: recording of the position of the hand in space (e.g., hand trajectory in space from using inertial systems or optical tracking of markers), or recording of hand joint angles (from using electrogoniometers or gauges-based instrumented gloves). When speaking of upper limb posture, the functional range of motion of arm joints [32] is commonly used both for clinical and biomechanics applications, which can be obtained from the direct recording of the arm joint angles or after processing position data of the arm segments. Analogously, active and functional range of motion assessment of each joint is often studied for the hand [18], especially for clinical assessment, although other global parameters such as the grip aperture [33] or the palm deformation [34] have been also proposed for biomechanics and prosthetics applications. Hand trajectory in space [35] has been also analysed in clinical and biomechanical studies, which requires collecting position-based data.

Table 2.2.5: Quantitative parameters commonly used to assess hand and upper limb posture. Examples of works that use it abbreviated as "REF.".

REF.	POSITION/POSTURE PARAMETER	ADDITIONAL INFO
[36]	Kinematics (posture), sEMG	Quantitative taxonomy based on GRASP taxonomy, both with posture and sEMG. Five basic movement categories based on the overall grasp shape, finger positioning and muscular activation
[37]	Hand joints mean posture	-
[18]	Hand joints range of motion - AROMs - FROMs	-AROMs: Computed as the difference between the maximum and the minimum joint angle recorded while performing in an active way the extreme postures. -FROMs: Computed as the difference between the P95 and the P5 joint angle recorded while performing tasks.
[33]	Grip aperture	Defined as the distance between the marker placed on thumb tip and that placed on the tip of the index finger (mm)
[34]	Palm deformation	Five little IMU sensors on the palm to detect palm shape (trough distal transverse, longitudinal and oblique arches) to estimate joint angles of middle, thumb and index fingers.
[32]	Shoulder, elbow and wrist FROMs	FROMs: Computed as the difference between the P95 and the P5 joint angle recorded while performing tasks.
[35]	Hand trajectory	Hand lateral deviation and vertical displacement.
[38]	Index of curvature	Ratio of the path length and the line-of-sight distance between the initial to the final endpoint position.

Parameters derived from kinematic data are frequently used as indicators of several motion properties. Table 2.2.6 presents the most commonly *velocity-related parameters* used to assess hand and upper limb kinematics. Some of them are related to speed and acceleration, such as duration [33], joint angular velocity [39], maximum and mean velocity of hand trajectory [40], time to peak speed [41], acceleration [42] or grasp opening velocity [43]). Those velocity-related parameters are commonly used as indicators of level of recovery in pathologies affecting manipulation [40], in product use characterisation [33], [44] or to study neural behaviour under different manipulation conditions [41], among others. Furthermore, hand joint velocities can also provide an indicator of the level of dexterity required to perform the task, as in tasks requiring static grasps joint velocities will be lower than in those requiring fine manipulation.

Table 2.2.6: Quantitative parameters commonly used to assess hand and upper limb velocity and acceleration. Examples of works that use it abbreviated as "REF.".

REF.	VELOCITY PARAMETER	ADDITIONAL INFO
[33], [40]	Duration (onset-offset)	Defined as the time interval between reach onset and offset (ms)
[40]	Velocity (maximum and average)	-
[39], [44]	Hand joint angular velocity (average)	-
[38]	Number of movement units (velocity peaks)	Movement unit considered as the difference between a minimum and the next maximum velocity value (of the tangential velocity profile of the hand) that exceeds the amplitude limit of 0.02 m/s.
[33]	Time of reach onset	Defined as the first time point at which the wrist velocity crossed a 20 mm/s threshold and remained above it for longer than 100 ms.
[33]	Time of reach offset	Time of reach offset defined as the time at which the wrist velocity dropped below a 20 mm/s threshold.
[40], [41]	Time to peak speed	The time from the start of the movement to peak speed.
[41]	Deceleration time	The duration from time to peak speed to the end of the movement.
[42]	Acceleration (max, average and range)	-
[44]	Hand joint angular acceleration (average)	Angular acceleration of hand joints (deg/s^2)
[40], [41]	Reaction time	The duration between a stimulus being presented and the speed exceeding a threshold level.
[43]	Grasp opening velocity	The peak velocity with which the thumb and index markers moved apart.
[45], [46]	Percent to peak grip aperture	Percent of time elapsed before the peak hand aperture was achieved.
[47]	Elbow angular peak velocity	-

Different parameters have been used as indicators of hand and upper limb motion *smoothness* (Table 2.2.7): the ratio between mean and maximum velocity [48], number of velocity peaks [49], zero crossings in acceleration profile [50], jerk [51] or the number of directional changes in hand's trajectory [52]. These parameters are usually proposed as indicators of recovery in patients with pathologies affecting manipulation, especially those affecting the neurological function such as cerebral palsy [49] or stroke [48].

Table 2.2.7: Quantitative parameters commonly used to assess hand and upper limb motion smoothness. Examples of works that use it abbreviated as "REF.".

REF.	SMOOTHNESS PARAMETER	ADDITIONAL INFO
[48]	Ratio between mean and maximum velocity	-
[49]	Number of velocity peaks	It's a quality measure of the movement smoothness computed from the speed profile of the movement hand.
[51]	Mean arrest period ratio	This metric is related to the movement smoothness. In people with movement disorders, while performing a movement toward an objective, several stops usually occur. This produces a movement with several submovements with several periods of practically zero velocity.
[50]	Zero crossings in acceleration profile	It measures the frequency of base line crossings in acceleration profile during the movement analysed.
[51]	Jerk	The rate of change of the acceleration profile during a movement. This is a measure computed from the third time derivative of position during the hand movement and represents a measure of non-smoothness quality characteristic.
[53], [54]	Spectral arc-length (redefined in other work in 2015)	As smooth movements are composed of low frequency components and a non-smooth movement is composed of higher frequency components, the use of Fourier Transform is adequate for the analysis of movement smoothness.
[52]	Number of directional changes in hand's trajectory	Normalized by the length of the task. A directional change is defined as a reversal in the sign of the first derivative of any of the three coordinates of the hand position.

Regarding *joint coordination*, principal component analysis has been used to identify hand [55] or arm inter-joint coordination [47] (Table 2.2.8). These analyses have been studied especially to characterise the hand motor control, and have been key in the field of robotic manipulation and prosthetics [56], in order to make affordable replicating human hand behaviour. Lately, other studies analysed hand synergies sparse in degrees of freedom [55], [57], analysing both task dependence of synergies and sharing of synergies across subjects, aiming also to contribute to fields such as hand function assessment or product design.

Table 2.2.8: Quantitative parameters commonly used to assess hand and upper limb motion coordination. Examples of works that use it abbreviated as "REF.".

REF.	COORDINATION PARAMETER	ADDITIONAL INFO
[55]	Hand joint synergies	This metric has sense in arm movements which involve several joints resulting in a coordinated movement.
[39]	Hand joint angular velocity synergies	Principal component analysis of hand joint angular velocities.
[47]	Shoulder and elbow synergies	Principal component analysis of shoulder and elbow joint angles.

When speaking of *efficiency/accuracy*, parameters such as path ratio [40], Fitt's index of difficulty and performance [58], trajectory error, [59], target error [60] or spatial overshoot [48] have been used (Table 2.2.9). These measures have been used to check motor recovery in patients with affected neurological function [40], [59].

Table 2.2.9: Qualitative parameters commonly used to assess efficiency/accuracy during grasping and manipulation. Examples of works that use it abbreviated as "REF.".

REF.	EFFICIENCY PARAMETER	ADDITIONAL INFO
[40]	Path ratio (%)	It's a measure of how directly the hand moves toward the target computed as the ratio between the length of the real subject's hand path and the length of the theoretical or desired trajectory.
[58]	Fitt's index of difficulty and performance	These metrics are measures of the movement quality computed from the time required to perform a reaching movement, the distance between the start and end points and the size of the object to reach to.
[59]	Trajectory error	It's a measure of the movement quality in terms of deviation of a subject's movement from a theoretical or desired trajectory. Similar to path ratio (Table 3.1.6)
[60]	Target error	This metric was computed as the maximum distance from the index finger to the target location at the end of the movement.
[48]	Spatial overshoot	It's a measure of the spatial excess, if occurs, in any direction of the movement, out of the limits described by the starting and the target location and quantifies movement accuracy.

Apart from the above-mentioned parameters, some others have been used to evaluate *bimanual performance*, such as movement overlap between both hands [61], goal synchronization [61], bimanual coupling [62], bimanual facilitation [62] and bimanual interference [63], which are detailed in Table 2.2.10. Again, these parameters have been used in literature mainly to assess performance in patients with affected neurological function such as cerebral palsy [61], [63] or hemiparesis [62].

Table 2.2.10: Quantitative parameters commonly used to assess bimanual performance. Examples of works that use it abbreviated as "REF.".

REF.	BIMANUAL PERFORMANCE PARAMETER	ADDITIONAL INFO
[61]	Movement overlap	Defined by the overlap time as a percentage of the total task completion time.
[61]	Goal synchronization	Defined by the time difference between, e.g.: one hand completing opening a drawer and the other starting to reach something inside the drawer.
[62]	Bimanual coupling	Analyses of times (reaching, reaction, performance) to determine the influence of increased task demands upon the coupling of the hands.
[62]	Bimanual facilitation	Analyses of times (reaching, reaction, performance) to determine whether performance asymmetries are decreased or eliminated when the two hands are required to perform functionally equivalent tasks.
[63]	Bimanual interference	Problems encountered when the two hands must each perform different movements or the same movement with different timing. Assessed with parameters such as task duration, movement overlap, spatial accuracy, etc.

Some of the above-presented kinematic parameters are based on joint angle data and their variation over time, while others are based on data representing positions in space of hand segments or markers and their variation over time. Both type of data could be obtained from data collected using motion capture techniques such as videogrammetry (which is available at the B&E research group). Nevertheless, as explained previously in this chapter, optical systems commonly present occlusion problems, especially when manipulating products. Therefore, videogrammetry was discarded for the experiments to be carried out in this thesis, and instrumented gloves were chosen instead. However, instrumented gloves only allow recording joint angles data over time, but not hand segments position in space. As a consequence, the analysis of parameters related directly with hand position in space (as those presented for analysing efficacy/efficiency), were discarded for the analyses carried out in this thesis. Nevertheless, as mentioned previously, in some analyses where analysing upper limb posture was considered important, a qualitative upper limb assessment method based in visual analysis (the RULA method [24]) was used alternatively.

Related parameters

The kinematics of the hand during grasping and manipulation is closely related to a long list of kinetic parameters which are beyond the studies carried out in this thesis (but not less important): those related with contact pressure (such as pressure distribution [64], range of grip pressure [52] or pressure-pain threshold [65], all detailed in Table 2.2.11), grip strength (such as directly grip strength measurements and pinch strength [66], finger push strength, pinch-pull strength, wrist-twisting strength, opening strength and push/pull strength [67], stability of precision grip forces [68], joint stress [69] or force synergies [70], all detailed in Table 2.2.12) or vibration [71]. Also beyond the scope of this thesis, it is particularly interesting to point out the literature studies focused on assessing muscle activation (such as surface electromyography [72], [73]) during grasping and manipulation, which can be correlated both with manipulation kinematics or kinetics.

Table 2.2.11: Quantitative parameters commonly used to assess grasping and manipulation contact pressure. Examples of works that use it abbreviated as "REF.".

REF.	CONTACT PRESSURE PARAMETER	ADDITIONAL INFO
[64]	Pressure distribution	-
[64]	Pressure distribution and EMG	-
[52]	Range of grip pressure	Defined as the maximum minus minimum pressure observed
[52]	Skewness	A measure of the asymmetry of the distribution of grip pressure, used to detect imbalances between the subject's ability to grip and to release the object.
[65]	Pressure-pain threshold	-
[74]	Subjective Rating of Perceived Exertion	-

Table 2.2.12: Quantitative parameters commonly used to assess grip strength. Examples of works that use it abbreviated as "REF.".

REF.	GRIP STRENGTH PARAMETER	ADDITIONAL INFO
[66]	Grip strength	-
[66]	Pinch strength	Measured with several pinch types: Tip pinch, key pinch, palmar pinch
[67]	Finger push strength	-
[67]	Pinch-pull strength	-
[67]	Wrist-twisting strength	Measured exerting a static twisting force in a clockwise direction on a variety of knobs and handles.
[67]	Jar opening strength (twisting)	Measured exerting a twisting force to unscrew a lid of a jar.
[67]	Push and pull strength	Measured exerting a static pushing or pulling force on a cylindrical bar.
[68]	Stability of precision grip forces	Calculated as the correlation between grip force and load force
[69]	Joint stress	Using finite element analysis
[75]	Multiaxis grip strength	-
[75]	Longitudinal center of pressure	-
[70]	Force synergies	Force synergies in multifingered grasps when changing objects' center of mass.

Other parameters focused in subjects' cognitive behaviour during grasping and manipulation have been proposed for product design purposes, such as gaze [73] (which can be assessed with special eye-tracking eyeglasses, equipped with eye cameras to record the eye movement and a camera recording the scene in front of the subject) or cognitive demand [76] (which can be assessed through a cognitive distraction test, in order to evaluate the cognitive load during the interaction with an object). Furthermore, as many of the parameters previously presented in this section, some works analyse and correlate several of them, such as muscle activation and gaze [73] or cognitive demand and hand posture [76].

Finally, related both with cognitive and physical abilities, there are some parameters that assess manual skills. Those parameters can be obtained from specific tests or from subjective questionnaires, and they are commonly used in clinical field of rehabilitation to assess functionality in patients with pathologies affecting upper limb function, being an indicator of recovery in the rehabilitation process. Table 2.2.13 presents an overview of the most common dexterity tests used in hand and upper limb assessment, and table 2.2.14 of the most common questionnaires to assess them (see specific references for more information regarding the test/questionnaire details and scoring).

Table 2.2.13: Dexterity tests commonly used to assess manual skills. Works that present it or use it abbreviated as "REF.".

REF.	DEXTERITY TEST
[77]	Functional Dexterity Test
[78]	Square Test
[79]	Jebsen Taylor Hand Test
[77]	Nine Hole Peg Test
[80]	Box and Block Test
[77]	Grooved Pegboard
[81]	Purdue Pegboard Test
[82]	Sollerman Hand Function Test (SHFT)
[83]	Minnesota Manual Dexterity Test (MMDT)
[84]	WorkAbility Rate of Manipulation Test (WRMT)
[85]	Standardizd Finger-To-Nose Test (SFNT)
[86]	Suitcase Packing Activity

Table 2.2.14: Dexterity questionnaires commonly used to assess manual skills. Works that present it or use it abbreviated as "REF.".

REF.	DEXTERITY QUESTIONNAIRE
[87]	Michigan Hand Questionnaire
[88]	Test D'évaluation Des Membres Supérieurs Des Personnes Âgées (TEMPA)
[89]	Disabilities of the Arm, Shoulder and Hand (DASH and QuickDASH)
[90]	Boston Carpal Tunner Syndrome Questionnaire (BCTQ)
[91]	Patiend-Rated Wrist (Hand) Evaluation
[92]	Functional Index for Hand Osteoarthritis/Dreiser
[93]	Australian Canadian Osteoarthritis Hand Index
[93]	Manual Ability Measure-36
[94]	Fugl-Meyer Assessment of the Upper Extremity (FMA-UE)
[95]	Movement Disorder Society Unified Parkinson's Disease Rating Scale
[96]	Bruininks-Oseretsky Test of Motor Proficiency
[97]	Adult-Assisting Hand Assessment Stroke Scale
[98]	Chedoke Arm and Hand Activity Inventory (CAHAI)

2.2.4 Kinematic databases

In literature we can find several works studying hand kinematics by means of computing the parameters presented in the previous section from experimental data recorded on human hands (an overview of these works is presented in the section 2.2.5). Even though, the majority of these works focused on the analysis of the performance of limited tasks, not being representative of the wide range of ADLs performed by human hand or the variety of existing products. Thus, in order to fill this gap, the tendency in the last years has been to provide large publicly available datasets of data collected (mainly kinematic data), in order to make data available to the research community, especially in the field of robotics and prosthetics. These datasets are key to apply artificial intelligence techniques such as artificial neural networks, in order to determine control algorithms based on human hand behaviour.

The nature of data provided in these datasets is varied and sometimes kinematic and kinetic data simultaneously collected are given. For example, some datasets provide sEMG signal data along with joint angles while performing specific hand movements and grasps [99], [100] or ADLs [101], others provide data such as sEMG and gaze [73] and others provide pressure distribution and grasp type (based in a specific taxonomy) while grasping several objects [102]. Nevertheless, given the purpose of this thesis, the datasets of interest are those providing hand kinematic data, and more specifically, continuous recordings of joint angles (or equivalent raw data).

In order to be representative of human hand behaviour (in order to characterise human hand function from a clinical point of view, to apply artificial intelligence techniques or to provide data to product designers, among others), datasets must contemplate a wide range of tasks representative of ADLs performed in a natural way, as well as a variety of products with different sizes and shapes. Furthermore, a representative sample of subjects has to be selected, considering subjects' sex, laterality or hand length. Apart from this, some technical aspects have to be considered, such as providing a continuous recording of data (especially in instrumental ADLs, where hand posture has more variability owing to the complexity of the tasks), considering the most appropriate units of given data depending on the purpose of the data collected or not only providing data from the dominant hand.

However, after reviewing some of the existing hand kinematic datasets publicly available and studying their characteristics (Table 2.2.15) it was observed that they are not representative enough of the variety of products (shapes and sizes) used to perform tasks by human hands most frequently, such as ADLs or manufacturing tasks.

Some of the experiments performed to create the existing datasets were carried out using a single object to perform a task [103], [116], while others used imaginary objects [104], [107], [112] (see Table 2.2.15). Furthermore, aiming to standardise objects used in grasping and manipulation experiments in the field of robotics, object sets such as the YCB [125] were proposed by researchers. Standardised object sets bring evident advantages to the scientific community devoted to grasping and manipulation research. Nevertheless, depending on the purpose of the study, in some occasions introducing a wider variety of objects, shapes and sizes may be interesting, while in other occasions (where the purpose is analysing the effect of product design) using similar products with changes in specific design features (e.g. several handle diameters or handle bending angles) will be required.

For this reason, defining (and providing) objects' properties such as lengths, weight and material is key when tailoring a dataset. Sometimes products' lengths are the only objects' specification given. Nevertheless, the importance of products' weight and material has not to be underestimated, as hand kinematics will depend on them [126].

Table 2.2.15: Main characteristics of publicly available datasets focused on hand kinematics. Dataset abbreviations: NTUA (National Technical University of Athens), UNIPI (Università di Pisa), ASU (Arizona State University), DLR (German Research Centre for Aeronautics and Space), TU Berlin (Technische Universität Berlin), HUST (Huazhong University of Science and Technology) and NINAPRO (Non-Invasive Adaptive Hand Prosthetics). Further information given in Table 4.2.1 in section 4.2.

Dataset	Objects	Tasks	Type of data
NTUA[103]	4	Static grasps, reach and grasp	Joint angles
UNIPI [104], [105]	Imagined	Static grasps	Joint angles
UNIPI-ASU [106], [107]	Imagined	Static grasps	Joint angles
DLR [106], [108]	23	Static grasps, reach and grasp	Joint angles
DLR [109], [110]	None	Static postures	Hand model
UNIPI [111], [112]	Imagined	Reach and grasp	Joint angles
UNIPI [111], [113]	None	Free space	Phase Space raw data
UNIPI [111], [114]	None	Free space	Phase Space raw data
TU Berlin 1 – IJRR [115], [116]	14	Static grasps, reach and grasp	CyberGlove raw data
UNIPI [111], [117]	2	Haptic exploration	Joint angles
HUST [118], [119]	14	Reach and grasp	Joint angles
TUB [120], [121]	25	Reach and grasp	CyberGlove raw data
UNIPI [122], [123]	21	Reach and grasp	Joint angles
NINAPRO [100], [124]	16	Static grasps/ postures	CyberGlove raw data

Regarding task selection to create a dataset, as explained previously, the tasks most frequently performed by human hand are ADLs, and they are key to personal autonomy. Nevertheless, the available datasets do not contain enough tasks to represent the wide variety of products used while performing ADLs. To do so, is important to cover both basic ADLs and instrumental ADLs, which allow including a wider variety of products with different design characteristics. Therefore, the sets of tasks analysed in this thesis are intended to cover some fields of ADLs where variety of objects with different sizes and shapes are used. Furthermore, the majority of datasets present tasks where specific guidelines were given to the subjects in order to perform specific grasps, controlling with it the interaction with the product. Thus, given the lack of datasets providing data of interaction with products in the most real way, tasks were asked to be performed in the most natural way, without asking subjects for any specific grasp type (which would condition subjects' hand kinematic behaviour). For our purpose, apart from covering a large part of tasks and product shapes, it is key to have a continuous recording of posture during all the manipulation phases, in order to study the overall effect of using it, and not only in the phase where a static grasp or manipulation is being performed, especially in instrumental ADLs, where hand posture presents more variations as they present more tasks implying fine manipulation. Some available datasets limit their data to static grasp postures [104], [107], [110] (see Table 2.2.15) providing valuable information for some applications but not allowing to quantify the effect of product shape or task performed.

Furthermore, another characteristic of hand kinematics datasets is the units of given data (see Table 2.2.15), which are presented as motion capture system raw data in many of the datasets available [113], [114], [116], [121], [124]. Despite the fact that raw data can be used for machine learning purposes, the same data given as anatomical angles would also allow the comparison of data collected using different motion capture systems. Furthermore, it would become more useful for applications to clinical evaluation or hand kinematics characterisation, as well as for product design.

Another important aspect when tailoring a hand kinematics dataset is participants' selection. In order to provide representative data of hand behaviour in the healthy adult population, it is important to take into account aspects such as percentage of right handed and left handed individuals, sex parity or variety of hand lengths. Nevertheless, available datasets provide data for a low number of subjects and with no variety of characteristics. Therefore, this aspect was considered because the studies framed in this thesis are intended to study the effect on the hand kinematics of a representative sample of users.

Moreover, all the datasets previously cited only provide data collected from subjects' dominant hand. In addition, despite the fact that some of the activities of daily living are usually performed using only one hand (e.g. drinking from a glass), others are commonly performed using one hand or both with almost the same frequency (i.e. carrying a dish), and others are bimanual (i.e. opening a bag of chips).

2.2.5 Reported results of hand kinematic analysis in ADLs and product manipulation

As observed in previous sections, several parameters have been used in literature to assess hand kinematics, and the studies performed are varied. In this section, a review of what has been already studied in literature is presented in order to identify important gaps to be addressed in this thesis, with the aim of contributing to the characterisation of hand kinematics during manipulation in ADLs. This review has been focused specifically on hand posture/motion analyses, which are more complex than the analysis of hand trajectories and provide relevant information regarding the clinical assessment of the hand itself, product design and robotics/prosthetics. However, the analysis of hand trajectories may provide complementary indicators, especially for a global analysis of the upper limb.

Qualitative posture-related analyses

The global analysis of hand kinematics requirements has been addressed in several studies in literature. Some of these studies focused on the analysis of grasp types, both in ADLs [2], [127], [128] and in workplace tasks [26], [129]. It is worth mentioning the study of the B&E research group [2] that analysed the frequency and duration of the different grasp types in ADLs on a representative sample of adult population, using the previously mentioned 9-class grasp taxonomy based on Edward's one [28] (Table 2.2.4 and Figure 2.2.18). For such purpose, ADLs representative of eight areas (food preparation, feeding, personal care, housekeeping, shopping, driving and transport, leisure and others) were analysed. In general, the grasp type more commonly used was the pinch one (Figure 2.2.19), and the field where this grasp type presented the highest frequency was food preparation. In the same way, intermediate grasp was more frequent in feeding and food preparation than in other fields.

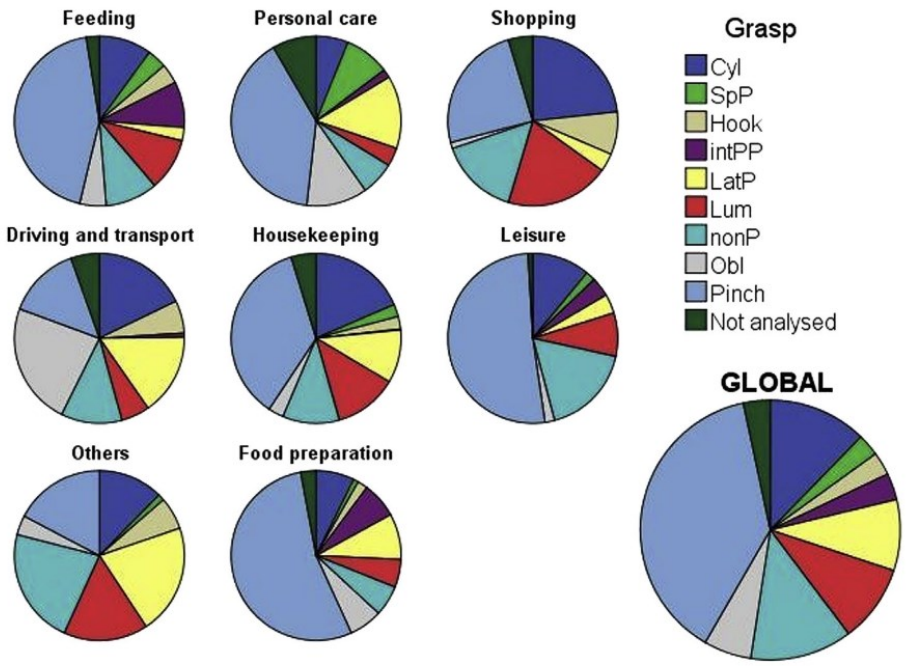


Figure 2.2.19: Distribution of daily frequencies of use of each type of grasp: total (bottom right) and by area of ADLs presented in [2]*. Grasp abbreviations as described in Table 2.2.4.*

A latter study of the B&E research group [127] assessed the importance of each grasp type for autonomy. To do so, the frequency of appearance of each grasp type in each ADL was weighted according to disability and dependency scales, determining with this its relevancy for autonomy. The most relevant grasps (considering both hands) were pad-to-pad pinch (31.9%), lumbrical (15.4%), cylindrical (12%) and special pinch (7.3%), together with the non-prehensile (18.6%) (Figure 2.2.20). These results are consistent with the previous work ones, where the pinch grasp was found to be the most used, presenting significantly higher frequency in fields such as feeding, personal care and food preparation, key for personal autonomy.

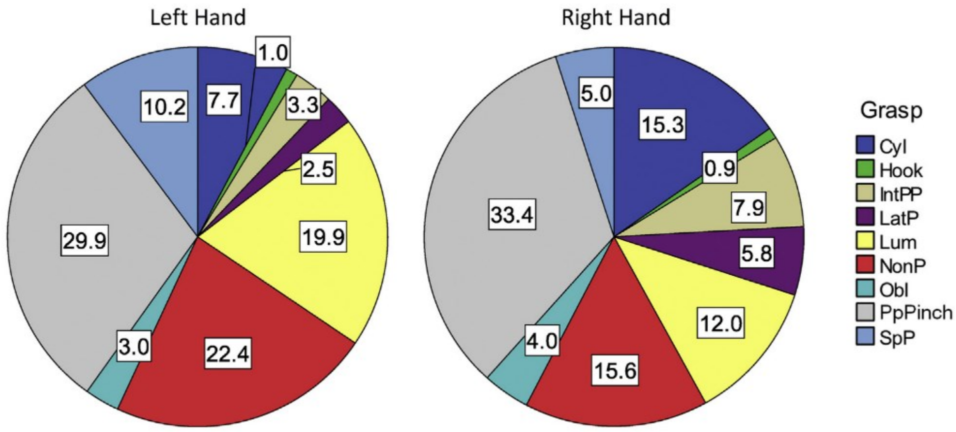


Figure 2.2.20: Relevance of the different grasp types presented in [127]*, distinguishing by hand. Grasp abbreviations as described in Table 2.2.4.*

Grasp type studies have been also carried out to analyse the effect of product characteristics (dimensions, stiffness, roundness and mass) while performing several tasks [130]. To do so, the authors analysed a dataset of video recordings of four subjects performing almost 10000 grasps [131], [132], providing descriptive data of grasp types performed when using different products (Figure 2.2.21). They found out, among other outcomes, that object shape and size were related with grasp type and grasped dimension (e.g. 96 % of grasp locations were in parts of the product with 7 cm or less in width). Outcomes like this can help to define requirements for hand rehabilitation and defines a reasonable grasp aperture size for a robotic hand. Furthermore, a tendency to grasp the smallest dimension of the object was observed in this work, what may contribute to better develop grasp planning algorithms in robotics. These outcomes should also be taken into account when developing products and hand tools, especially when conceiving assistive devices that intend to mitigate the effect of certain pathologies that reduce manipulation capabilities.

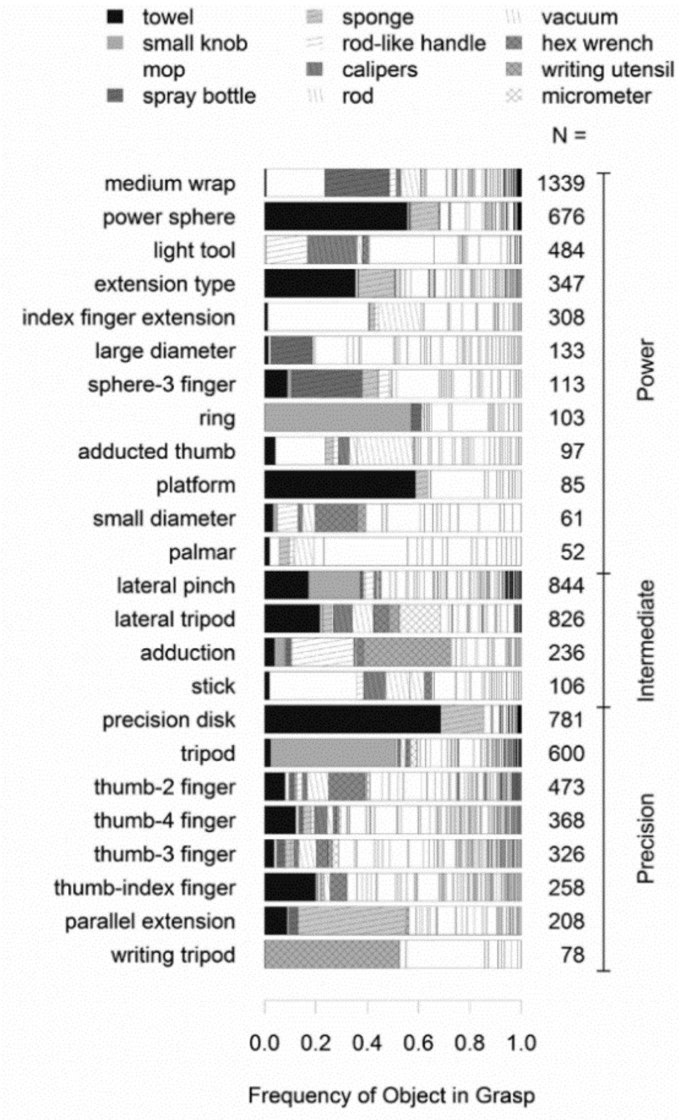
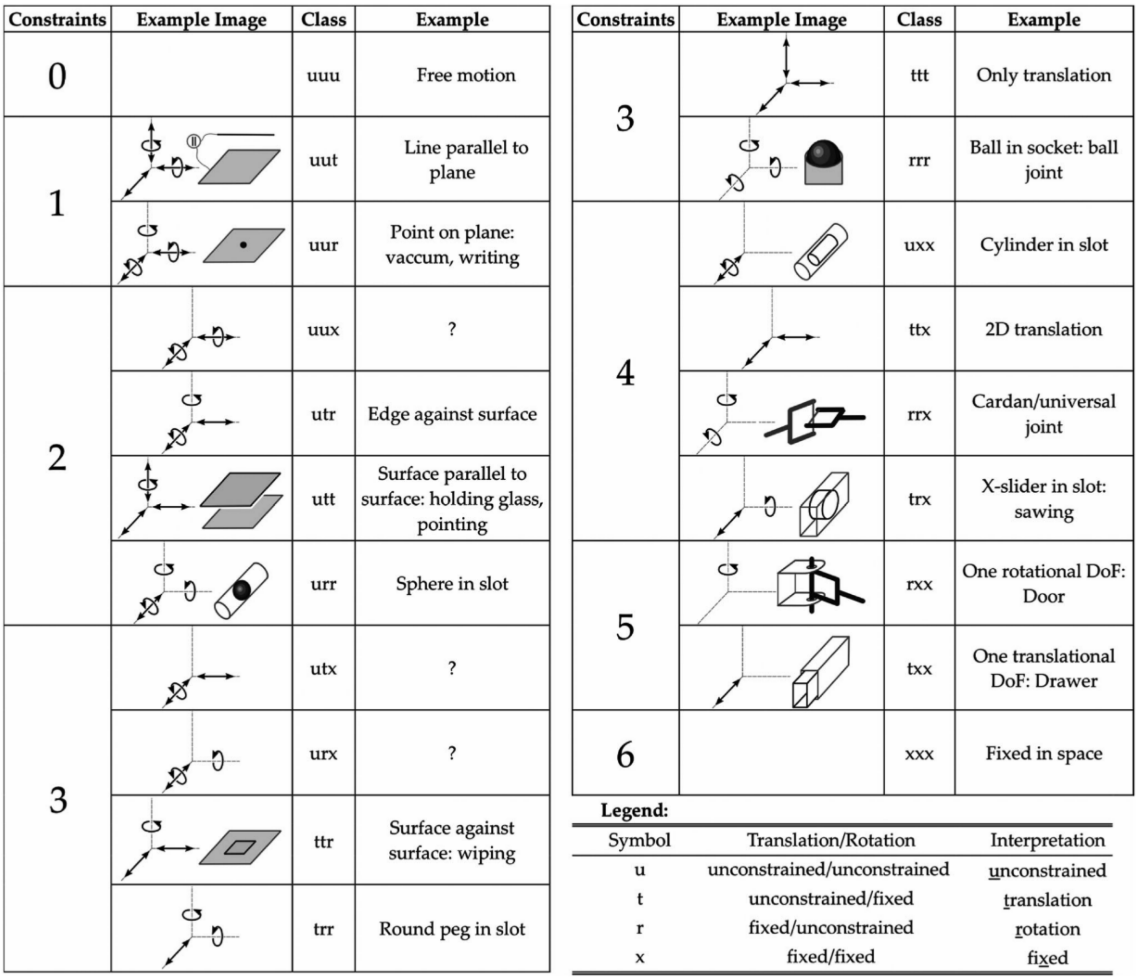


Figure 2.2.21: Plot of the general object and grasp type frequencies, being the 12 most common objects used highlighted (the rest of the objects are indicated in white separated by vertical lines). Grasps with frequencies lower than 50 were not plotted. Figure extracted from [130].

Later on, the same authors published another work using the same experimental data, but correlating the observed results of objects and grasp types with task properties [128]. They selected certain tasks from the datasets [131], [132] and assigned them three characteristics: force (which could be "weight" —when object was lifted— or just "interaction" —when it was not—), constraints (if movement was free, in a plane, etc. (Figure 2.2.22)) and functional class (which could be "hold", "use" and "feel"). Then, frequencies of grasp types when tasks presented each of these characteristics were presented (Figure 2.2.23), along with a plot of grasp type frequencies for each object type (similar to the one presented in Figure 2.2.21). Then, data from both analyses was correlated in a table (Figure 2.2.24), along with other parameters such as grasped dimension, grasp size or object properties. These frequency analyses, along with other analyses and outcomes along the work, provided a characterisation of the objects we interact with, the tasks we perform and the grasps we use for them.



Constraints	Example Image	Class	Example
0		uuu	Free motion
1		uut	Line parallel to plane
		uur	Point on plane: vaccum, writing
2		uux	?
		utr	Edge against surface
		utt	Surface parallel to surface: holding glass, pointing
		urr	Sphere in slot
3		utx	?
		urx	?
		ttr	Surface against surface: wiping
		trr	Round peg in slot
3		ttt	Only translation
		rrr	Ball in socket: ball joint
4		uxx	Cylinder in slot
		ttx	2D translation
		rrx	Cardan/universal joint
		trx	X-slider in slot: sawing
5		rxx	One rotational DoF: Door
		txx	One translational DoF: Drawer
6		xxx	Fixed in space

Legend:

Symbol	Translation/Rotation	Interpretation
u	unconstrained/unconstrained	unconstrained
t	unconstrained/fixed	translation
r	fixed/unconstrained	rotation
x	fixed/fixed	fixed

Figure 2.2.22: Figure extracted from [128] *with the task constraints considered (adapted from* [133]*, where a set of 20 possible relative motions between two rigid bodies are specified).*

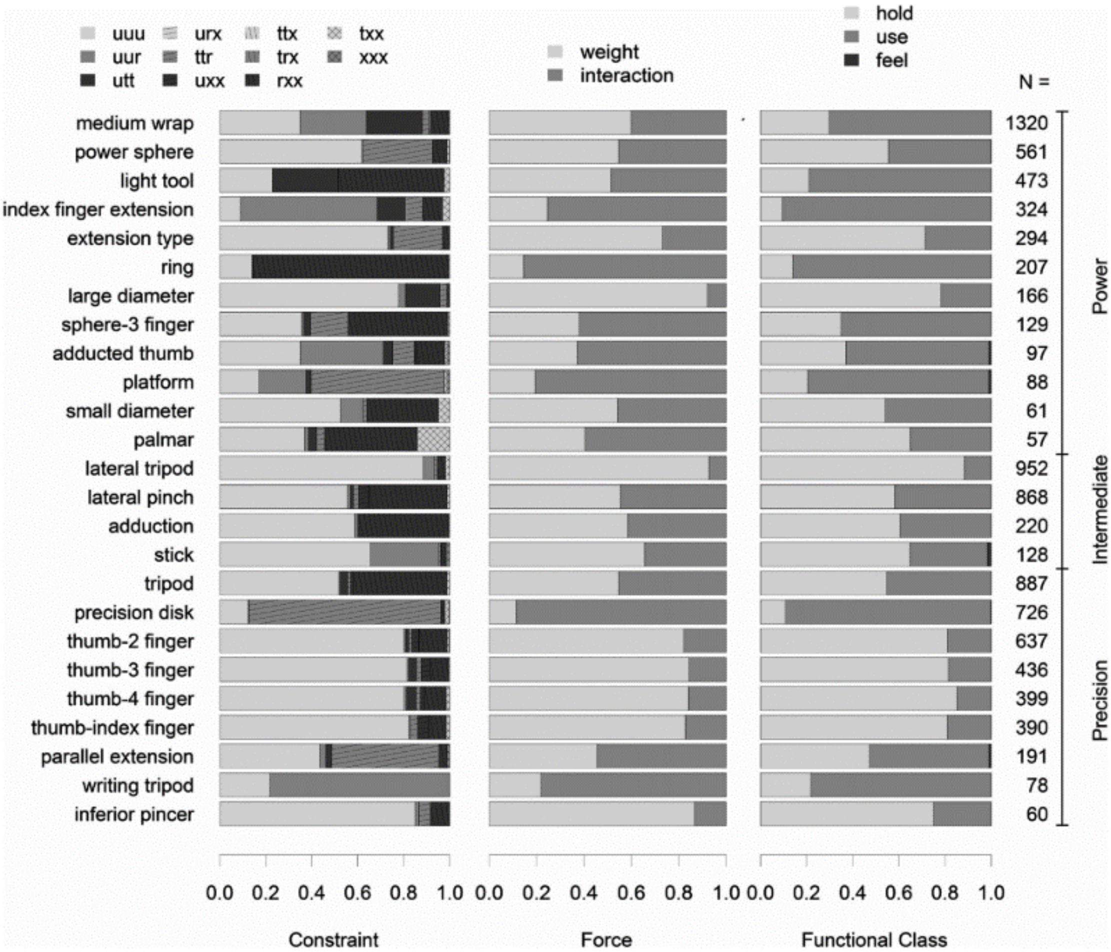


Figure 2.2.23: Plot of the general task characteristics and grasp type frequencies, being the 12 most common objects used highlighted (the rest of the objects are indicated in white separated by vertical lines). Grasps with frequencies lower than 50 were not plotted. Further information regarding task characteristics detailed in the original article [128]. *Figure extracted from* [128].

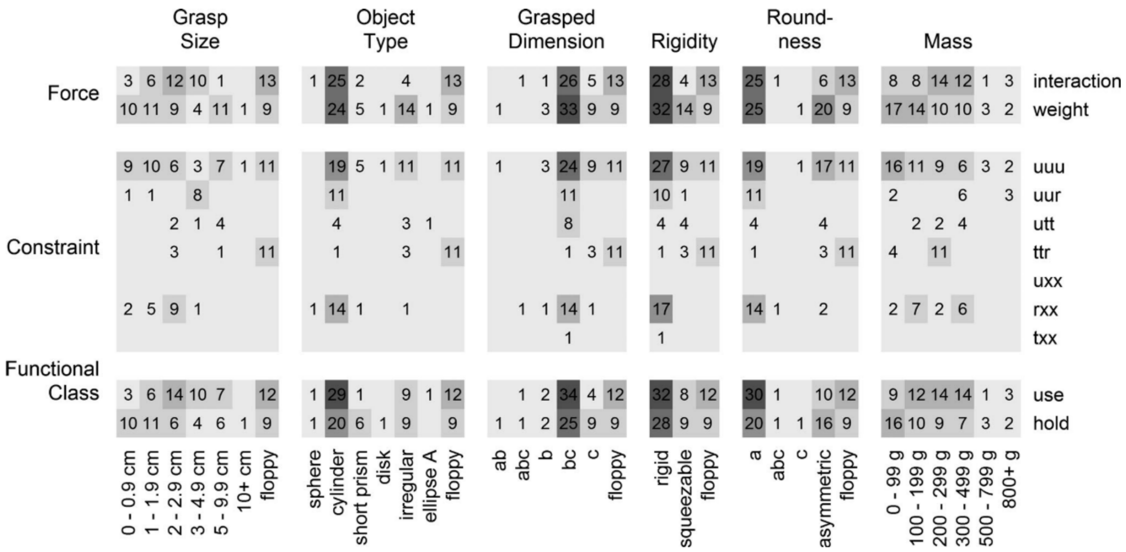


Figure 2.2.24: Relationship between the task and the object properties. Each of the boxes sum up to 100 percent and expresses the relationship between one task attribute and one object attribute. Darker background indicates a higher percentage. Figure extracted from [128].

Other works have studied the grasp type performed by thumb and index finger depending on certain products' design characteristics and subjects' hand characteristics [134]. They found out that the use of precision-pinch grasp gradually decreased with the increase of the object's diameter, oppositely to what it is observed for the power-grasp case. Furthermore, the shorter the finger-length of the participant was, the more likely the participant was to select the power-grasp for grasping an object compared to the precision-pinch. Apart from this, grasp type has been also found to vary when grasping objects in different locations, orientations and shapes [135] (e.g. participants most frequently held cylindrical and square pillar objects using cylindrical grasp and five finger pinch, respectively).

Quantitative posture-related analyses

A wide variety of quantitative parameters to assess hand posture during reaching and manipulation have been used in literature, as seen in previous sections. This thesis intended to consider all the phases of the manipulation process, from reaching to release. Nevertheless, given the importance in the robotics field of planning the most appropriate approach to the target object to ensure the success of the grasp, several works in literature have focused especially in hand preshape during reaching phase, analysing postural quantitative parameters such as hand joint angles [136] or grasp opening [33], among others, revealing a relationship between these parameters and target object properties.

Despite this variety of parameters, this thesis is focused on those related with hand joint angles, in order to assess entire hand posture. In this sense, parameters such as functional range of motion (FROM) or mean postures have been studied in literature during the performance of ADLs [18], [137]–[139] or manufacturing tasks [140], among others. While FROM gives an overview of the required hand mobility to perform the tasks, mean postures provide data regarding the most representative posture of each hand joint during task performance. Some studies [137] have analysed FROM in standardised hand function tests such as the Sollerman Hand Function Test, which was conceived to be representative of ADLs in clinical assessment, while other works have considered a variety of ADLs from different fields [18], [138], [139]. It is worth mentioning the previous study of the B&E research group [18], which identified the FROM required in a set of 24 representative ADLs from four different fields (communication, mobility, self-care and domestic life), selected to cover all the areas of the ICF chapters most directly related with hand function (excluding some specific tasks that were not possible to perform while wearing an instrumented glove, such as taking care of animals). The results obtained from this work are presented in Table 2.2.16, where FROMs were computed as the P95 and the P5 joint angle recorded while performing tasks.

Table 2.2.16: Global FROM (SD) obtained for each joint and movement, in degrees.

DIGIT	JOINT	MOTION	FROM (SD)
Thumb	CMC	Flexion	-11.2 / 33.9 (12.8) / (10.4)
	MCP	Flexion	-17.1 / 14.3 (6.8) / (7.8)
	IP	Flexion	-7.2 / 80.6 (14.5) / (23.4)
Thumb-Index	CMC	Abduction	5.4 / 21.2 (2.6) / (4.0)
Index	MCP	Flexion	-1.8 / 51.5 (10.2) / (9.8)
	PIP	Flexion	4.6 / 88.9 (7.1) / (13.6)
Index-Middle	MCP	Abduction	-7.3 / 16.0 (2.8) / (3.4)
Middle	MCP	Flexion	-1.3 / 62.7 (10.1) / (13.5)
	PIP	Flexion	8.3 / 78.3 (4.6) / (7.6)
Middle-Ring	MCP	Abduction	-13.7 / 2.2 (3.0) / (3.5)
Ring	MCP	Flexion	-5.5 / 60.8 (6.6) / (11.5)
	PIP	Flexion	9.3 / 91.1 (5.9) / (7.8)
Ring-Little	MCP	Abduction	-8.1 / 10.6 (3.1) / (4.4)
Little	MCP	Flexion	-5.4 / 71.0 (6.0) / (8.2)
	PIP	Flexion	6.6 / 84.5 (6.4) / (9.8)
Palm	PalmArch	Flexion	-5.2 / 29.8 (8.5) / (9.7)

FROM along with mean posture have been also used to analyse the kinematics requirements for performing separately several ADL, such as in [141], where grasping a glass, a ball pen, a key and a knife were studied, or in [142], where the task of throwing a baseball (comparing postural parameters obtained in three different types of pitch) was performed. Another work analysed FROM and mean postures while performing a set of 11 ADLs [138], but in this case considering firstly all the tasks together and lately grouping it in four groups, depending on the grasp performed (key pinch, tip pinch, precision grip and power grip), not finding statistically significant postural differences between groups of tasks. Furthermore, the effect of the task performed in hand posture has been analysed by comparing the performance of different tasks using the same product, as in [143], where subjects were asked to perform five tasks with the same bottle: (1) grasp it, (2) lift and throw it, (3) pour water into a container, (4) place it accurately in a specific area, (5) pass it to another person. This work found out that task performed significantly affected posture, both in reaching and grasping phases. Other works, aiming to compare both hand performance while performing a specific ADL (using a keyboard) [44], analysed (among other velocity-related parameters) mean postures.

Postural parameters were also compared when using products with different design characteristics. For example, the task of eating with spoon was performed using adapted spoons (assistive devices) with different handle diameter [144], observing lower FROM values in finger metacarpophalangeal and proximal interphalangeal joints (metacarpophalangeal and interphalangeal in the case of thumb) when using products with higher handle diameters. Others also analysed the postural effect when performing the same grasping task with cylinders and square pillars, but changing its size, weight and grasp type. They found out that grasp type and object size affected the joint flexion angles more significantly than did object shape (cylinder or square pillars) and weight. Only certain joints were affected by object shape, and joint angles were found to increase linearly as the object size decreased.

These last works, as well as the above-mentioned ones that have studied grasp type when using products with different characteristics [26], [130], [134], evidence an effect of products' design on hand posture. A deeper and more detailed analysis of how product's design affects hand kinematics would be worthy. Studying the effect of products' shape on hand kinematic parameters can provide important information to product designers and ergonomists. Nevertheless, owing to the complexity of studying quantitative hand joint kinematic parameters, the tendency in product ergonomics assessment has been studying qualitative kinematic parameters (as presented previously) or kinetic parameters such as grip strength [145]. In this sense, analysing quantitative posture parameters such as FROM or mean postures when performing tasks using products with different characteristics (not only reducing it to specific products as spoons) would provide important information regarding the effect of certain product design characteristics, contributing to the design of more inclusive products. Furthermore, it would help therapists with the assistive device prescription process, as they would be able to prescribe specific products for certain pathologies, as they would know their effect on hand kinematics. In the same way, analysing it when performing tasks using a wide variety of products would contribute to the knowledge of healthy hand behaviour during ADLs performance.

Velocity-related analyses

Studying velocity-related parameters of hand motion during reaching and manipulation is a very common practice, especially in the field of rehabilitation. Nevertheless, the majority of these studies are focused in analysing hand motion in space through parameters such as linear velocity or smoothness [146]–[149], as hand trajectory in space is easier to record than hand joint kinematics. Parameters such as trajectory smoothness have been used as measures of motor performance, both in healthy subjects and patients with impairments related with motor control and musculoskeletal system

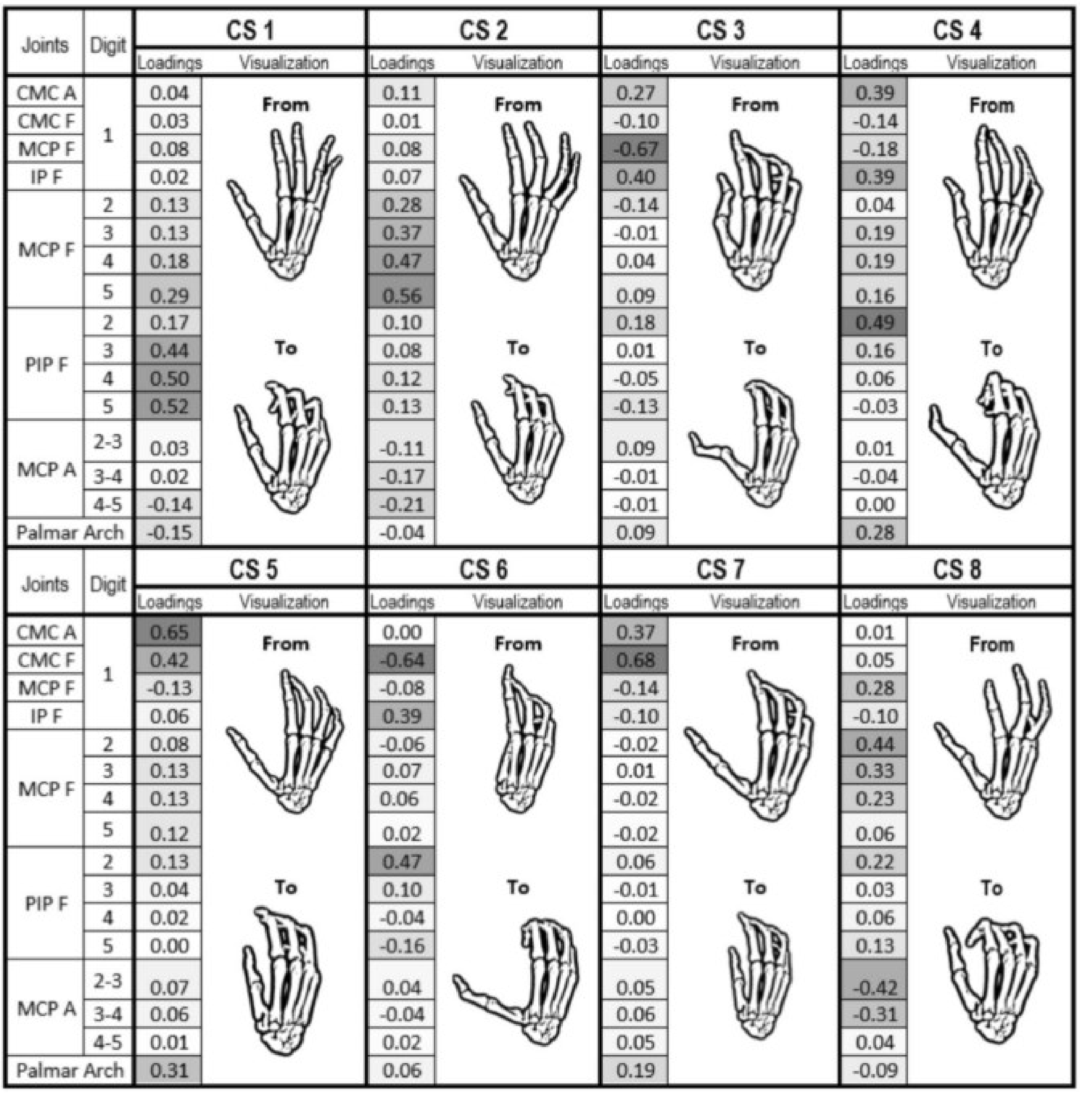
[150]–[152]. In fact, some works analysed hand motion in patients recovering from stroke and other motor related impairments, revealing that trajectory smoothness was lower and movements were more segmented than in healthy subjects [51], [153]. In the same line, some works analysed measures such as jerk or velocities while healthy subjects were performing ADLs using certain products, in order to correlate those parameters with the dexterity required to manipulate the product, as in [154]. In that work, velocities and jerk were calculated during packaging interactions and the performance of the dexterity test Purdue Pegboard Test, finding out that speed and jerk were not correlated with the perceived level of dexterity.

Nevertheless, fewer works are focused in velocity-related parameters of specific hand joints. An early work analysed the performance of rapid finger-thumb grasps in order to evaluate motor planning, finding out that joint angular velocities of these fingers were relatively constant across trials and presented bell-shaped profiles, while joint angles and fingertip trajectories were highly variable [155]. Later on, they also studied the effect of movement speed on kinematics of these two fingers. In this case, they found out that in contrast of the bell-shaped velocity profiles that presented joints while performing high-velocity movements, profiles with several submovements with multiple peaks were obtained when performing slower grasps [156]. Furthermore, they also found out that variability of index finger and thumb joint end-positions did not increase with speed. Other works compared joint velocity while performing two tasks (closing the fist and grasping a ball) in healthy subjects and subjects with stenosing tenosynovitis [157], finding out significant decrease in maximum joint velocities in pathological hands. Some studies analysed it while performing a single ADL, such as the work previously cited work [44] comparing both hand kinematics while using a keyboard. This work, apart from comparing mean postures also analysed mean angular velocities and accelerations. Apart from this, other works analysed time varying kinematic synergies of hand joints, studying hand joint velocities in several conditions such as reach and grasp tasks [158], precision-grip movements [159] or rapid grasping tasks [160]. Nevertheless, hand joint angular velocities (as well as other velocity-related parameters) have not been as deeply analysed in literature as posture-related parameters. For this reason, given the gap in literature regarding these types of analyses, studying velocity-related parameters (as mean velocities, ranges of velocities, acceleration or smoothness) during task performance using products with several characteristics would be interesting in order to characterise healthy hand kinematic requirements (both when performing tasks from several fields of ADLs or using products with certain design characteristics) and to assess recovery level from pathologies.

Kinematic synergies analyses

Human hand kinematic behaviour is complex and presents a large number of DoF. Nevertheless, there is an evidence of coordination patterns owing to mechanical and neurological couplings [161], [162]. Taking advantage of this coordination, several works in literature [55], [57], [106], [122], [163] have studied postural synergies in order to reduce hand kinematics dimensionality using principal component analysis (PCA), which is the most commonly used method for this purpose. These studies simplify the number of DoF required to define human hand behaviour in several conditions, such as grasping 57 imagined objects [106], grasping cylinders with different diameter and weight [163] or ADLs performance [55], [57], among others. Nevertheless, most works in literature were mainly conceived aiming to analyse strategies of motor system in hand posture control and to provide data to researchers devoted to grasping robotics and prosthetics [106], [122], applying a PCA method that did not take into account the DoF with small range of motion and not looking for sparse synergies in DoF. On the contrary, recent studies from the B&E research group, which were more focused in clinical decision-making and rehabilitation, proposed applying a different PCA method to obtain sparse synergies and not hiding the importance of DoF with small range of motion [55], [57], [163]. The first work analysed static postures while grasping cylinders with different diameter and weight [163], revealing five main synergies: digit arching (flexion of proximal interphalangeal joints), closeness (coordinated flexion and abduction of metacarpophalangeal finger joints), palmar arching, finger abduction and thumb opposition. They also found out that object's weight only affected kinematics of precision grasps, while diameter affected both power and precision grasp kinematics. Furthermore, another work from the group [57] analysed synergies both in reaching and manipulation phases separately during the performance of 26 representative ADLs, most of them extracted from the Sollerman Hand Function Test. Five main synergies explaining 75% of variance were revealed: closeness (coordinated flexion and abduction of metacarpophalangeal finger joints), digit arching (flexion of proximal interphalangeal joints), palmar-thumb coordination (coordination of palmar arching and thumb carpometacarpal flexion), thumb opposition, and thumb arch. It was observed that the first two synergies were common to all the tasks, what they identified as *gross motion* (the more basic patterns of finger motion). Nevertheless, the rest of synergies were differently combined across tasks, what they called *subtle motions* (the more specific patterns). Later on, another study from the group [55] analysed the sharing of those synergies across subjects while performing a set of 24 representative ADLs from different fields, also applying the same PCA method to kinematic data collected for each subject, revealing eight core synergies (Figure 2.2.25): the first two (implying PIP flexion and MCP flexion, respectively), which were shared across all the subjects, and the rest, which were combined in different way across subjects.

Then, it can be summarized that the first two core synergies (flexion of PIP and flexion of MCP) were obtained in studies analysing ADLs or product use [55], [57], [106], [163], independently of the variety of tasks selected and products used, revealing an evident finger flexion coordination, both in MCP and in PIP joints. Nevertheless, the rest of kinematic synergies were found to be task dependent, and diameter and weight of cylindric objects was found to affect hand kinematics, suggesting that analysing kinematic data while performing different tasks and using different products would be worthily, contributing to analyse hand kinematic requirements while performing certain fields of tasks or using products with specific characteristics.



Joints	Digit	CS 1 Loadings	CS 2 Loadings	CS 3 Loadings	CS 4 Loadings	CS 5 Loadings	CS 6 Loadings	CS 7 Loadings	CS 8 Loadings
CMC A	1	0.04	0.11	0.27	0.39	0.65	0.00	0.37	0.01
CMC F	1	0.03	0.01	-0.10	-0.14	0.42	-0.64	0.68	0.05
MCP F	1	0.08	0.08	-0.67	-0.18	-0.13	-0.08	-0.14	0.28
IP F	1	0.02	0.07	0.40	0.39	0.06	0.39	-0.10	-0.10
MCP F	2	0.13	0.28	-0.14	0.04	0.08	-0.06	-0.02	0.44
MCP F	3	0.13	0.37	-0.01	0.19	0.13	0.07	0.01	0.33
MCP F	4	0.18	0.47	0.04	0.19	0.13	0.06	-0.02	0.23
MCP F	5	0.29	0.56	0.09	0.16	0.12	0.02	-0.02	0.06
PIP F	2	0.17	0.10	0.18	0.49	0.13	0.47	0.06	0.22
PIP F	3	0.44	0.08	0.01	0.16	0.04	0.10	-0.01	0.03
PIP F	4	0.50	0.12	-0.05	0.06	0.02	-0.04	0.00	0.06
PIP F	5	0.52	0.13	-0.13	-0.03	0.00	-0.16	-0.03	0.13
MCP A	2-3	0.03	-0.11	0.09	0.01	0.07	0.04	0.05	-0.42
MCP A	3-4	0.02	-0.17	-0.01	-0.04	0.06	-0.04	0.06	-0.31
MCP A	4-5	-0.14	-0.21	-0.01	0.00	0.01	0.02	0.05	0.04
Palmar Arch		-0.15	-0.04	0.09	0.28	0.31	0.06	0.19	-0.09

Figure 2.2.25: Core synergies (abbreviated as "CS") loadings along with their Opensim representation ordered by percentage of subjects in each cluster and mean percentage of variance explained per cluster. Digit and DoFs labelled as explained in section 2.2.1.

Apart from PCA, methods such as correlation between joint angles have been used in literature in order to study finger motion coordination during product manipulation tasks such as packaging interactions [154]. In fact, this work compared (among other kinematic parameters) correlations between finger joints during packaging interactions and during the performance of the Purdue Pegboard Test, finding out that perceived required dexterity to perform the tasks was highly dependent of correlation between finger joints, perceiving less requirement of dexterity when fingers correlation was higher.

2.3 Conclusions

The ability to perform activities of daily living (ADLs) is key to ensure a full and autonomous life [164]. In fact, ADLs are the tasks most frequently performed by human hand, involving a wide variety of products with different shapes and design characteristics. Nevertheless, people with pathologies or disabilities affecting upper limb and hand mobility experience difficulties to accomplish ADLs using standard products, affecting their personal independence.

As explained, human hand behaviour is complex, and the product manipulation that takes place during ADLs performance is composed by several phases that have been studied in literature for several purposes (clinical assessment, product ergonomic design, robotics, etc.). Thus, the kinematic parameters that have been used in literature to assess hand kinematic behaviour are varied, from qualitative parameters such as grasp taxonomies, to quantitative ones. Nevertheless, some quantitative parameters have been used mainly to assess kinematics of hand trajectory in space, rather than specific joint kinematics.

It has been observed that some works in literature analysing both qualitative and quantitative parameters revealed an effect of products' characteristics on hand posture. Nevertheless, as explained, these studies were not performed considering a wide range of ADLs using a variety of products representative of the ones that human hand interacts with. Therefore, using grasp taxonomies or quantitative posture-related parameters as FROM or mean postures when performing tasks using products with different characteristics would provide important information regarding the effect of certain product design characteristics on hand posture. Furthermore, joint angular velocities (as well as other velocity-related parameters) have not been as deeply analysed in literature as posture-related parameters. Therefore, given the gap in literature observed in this type of analyses, studying velocity-related parameters (as median velocities, peak velocities, acceleration or smoothness) would be useful to characterise the hand kinematic requirements when using certain products. Quantifiable information regarding the effect of overall product shape or specific modifications (e.g. thickened or bended handles) would be key to product designers when developing assistive devices or ergonomic products. Being able to conceive product designs that require more neutral postures or lower joint velocities would especially benefit those mentioned users with pathologies or disabilities affecting upper limb and hand mobility. For this reason, in this thesis I present two contributions in this line, comparing hand and upper limb kinematics while using normal products and assistive devices, analysing both quantitative and qualitative kinematic parameters. The first one is more focused in upper limb posture and grasp classification, while the second one analyses hand joint kinematic parameters such as mean postures, ranges of motion, velocities and smoothness.

Human hand kinematics depend on the level of recovery for certain pathologies affecting upper limb mobility. Several works analysed hand kinematics of patients with affected manipulation capabilities, but usually by means of parameters assessing hand trajectory in space, rather than specific joints, as mentioned previously. Several works in literature aimed at characterising hand joints kinematic behaviour by presenting normative values of several kinematic parameters, such as FROMs or mean postures, but fewer works analysed hand joint velocity-related parameters, which would provide reference values for healthy hand kinematic behaviour through additional quantifiable indicators, as velocity-related parameters of hand trajectory in space during ADLs were found to be an indicator of recovery in rehabilitation processes.

In order to characterise healthy hand kinematic behaviour it is key to analyse the tasks most commonly performed, which are, as mentioned, ADLs. Nevertheless, hand kinematics was found to be dependent to task performed, both in studies analysing grasp types and kinematic parameters (such as FROMs or postural synergies, among others). Therefore, it would be interesting to identify groups of similar tasks and analysing several posture-related and velocity-related parameters for these groups, in order to go deeper in the characterisation of healthy hand behaviour during ADLs.

Nevertheless, for these analyses, large datasets of kinematic data while grasping a wide variety of objects with different characteristics are required. Therefore, having also observed a gap in hand kinematics dataset available for such purpose, another contribution of this thesis is the KINE-ADL BE-UJI Dataset. This dataset contains kinematics data of 20 subjects performing cooking and feeding ADLs using 66 different objects. After this, tasks from the dataset were classified into several groups and normative values of postural and velocity-related parameters were provided. These results contribute to characterise healthy hand behavior, as well as to identify the task groups that would be difficult to perform by people with affected hand function, as they required less neutral postures or higher velocities.

After having observed all the mentioned gaps in kinematic analysis and having planned the experiments, the most suitable motion capture technique for hand joint kinematics recording was chosen to be the instrumented glove CyberGlove. These gloves do not present problems when manipulating objects (as occlusions in optical systems), do not have data interferences when using it near to ferromagnetic objects (as happens when using electromagnetic systems) and the easiness of its setup is not comparable with other systems. Nevertheless, before performing all the product manipulation experiments, some validation tests were performed using these gloves, as we had several concerns regarding its performance. These validation experiments are also presented in this thesis as a piece of advice to researchers using this motion capture system, Firstly, the effect of their use on manipulation dexterity at different levels of precision was tested. After this, the reliability of using these gloves to measure DIP joints using a 22DoF glove was studied, as well as the possibility of estimating these joints kinematics from proximal interphalangeal joints motion, both in manipulation conditions and in free motion. Finally, given the importance of distinguishing free motion from manipulation in hand kinematic analyses, the precision of detecting contact with objects using an instrumented glove equipped with pressure sensors and performing visual analysis using the instrumented glove CyberGlove was compared, as well as the precision of kinematic recording using both gloves.

Therefore, this thesis presents all these validation experiments to check the functioning of CyberGlove instrumented gloves. Later on, the KINE-ADL BE-UJI Dataset and characterise healthy hand kinematic behaviour when performing different groups of tasks is presented. Finally, the effect of products' design characteristics on hand kinematics, both qualitatively and quantitatively is analysed. These experiments presented in this thesis intended to contribute to hand kinematic characterisation during product manipulation in ADLs, aiming to enlarge progressively the variety of products and tasks considered in future experiments.

Chapter 3

Using instrumented gloves in hand kinematics recording while manipulating products

3.1 Introduction

Hand and upper limb kinematics has been widely studied in literature owing to the importance it has in different fields of study such as workplace ergonomics [165], product design [166], clinical rehabilitation [47] or robotics [167]. The methods used to acquire kinematic or postural data from hand or upper limb are varied, from motion capture systems (electrogoniometers [144], instrumented gloves [37], videogrammetry [168], etc.) to manual techniques based on visual inspection [169]. Selecting the most suitable one will depend on factors such as the parameters to be studied, joints of interest, experiment environment, objects used in the experiments (if any) or required data precision, among others.

The studies presented in this thesis have been performed using both manual techniques based on visual inspection and motion capture techniques. A visual classification was considered for a gross analysis of the upper limb postures (depending on the degree of flexion/extension and abduction/adduction of each arm joint), as well as for identifying grasp types according to a specific taxonomy. However, for a thorough kinematic analysis of joints at hand level (ROM, velocities, mean postures, etc.), a motion capture system was required.

Electromechanical instrumented gloves commonly use extensiometric gauges, which are placed over the joint intended to study. The signal provided by each gauge (in mV) varies depending on its flexion. Nevertheless, in order to correlate this voltage variation with the joint angle, a calibration process is required to calculate the gain of each specific gauge.

The instrumented gloves used in this thesis are CyberGloves (CyberGlove Systems, San Jose, CA, USA). These gloves are the most used in biomechanics and the B&E research group had already experience using them. They are made of a synthetic elastic mesh fabric on the palmar side, and a denser synthetic elastic fabric on the back in which the extensiometric gauges and the wiring are embedded (Figure 3.1.1). The number of degrees of freedom (DoF) that the glove measures will depend on the gauges it has embedded. In this case, there is a model that measures 18 DoF (from wrist, thumb carpometacarpal, palmar arch, metacarpophalangeal and proximal interphalangeal joints (PIP)) (Figure 3.1.2A), and another that measures 22 DoF, which allows also recording the distal interphalangeal joints (DIP) (Figure 3.1.2B). Therefore, the kinematic model behind the calculations presented in this thesis and the DoF considered in each joint (as well as the abbreviations used in the entire thesis) are graphically represented in Figure 3.1.3.

Figure 3.1.1. Palm and back of the CyberGlove instrumented glove.

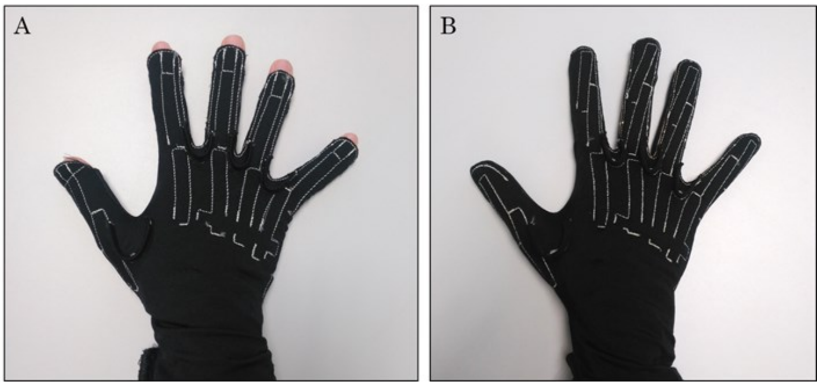


Figure 3.1.2. CyberGlove instrumented gloves. (A) 18DoF model, (B) 22DoF model.

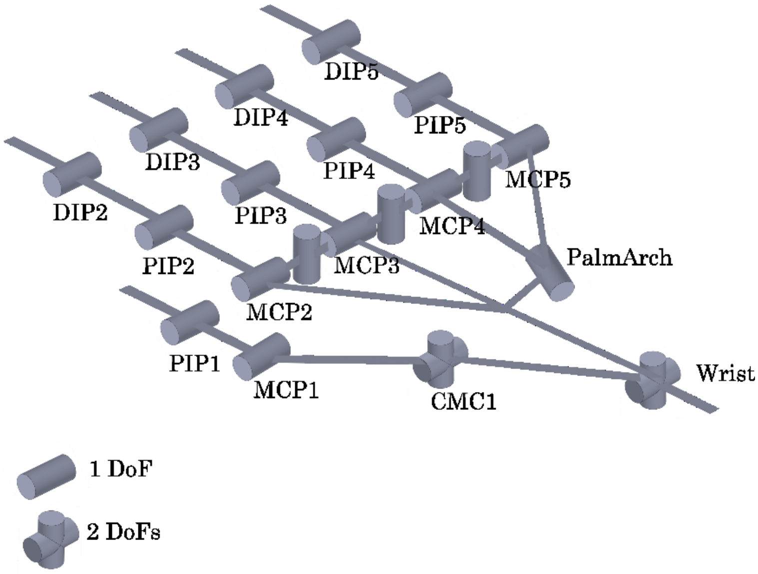


Figure 3.1.3. Hand kinematic model used in this thesis, based on the location of gauges in CyberGlove instrumented gloves. Joint abbreviations: PalmArch for palmar arch, CMC for carpometacarpal, MCP for metacarpophalangeal, PIP for proximal interphalangeal, DIP for distal interphalangeal. Model of 18DoF without considering DIP joints, model of 22DoF considering it.

A specific calibration protocol for the 18 DoF model was developed previously by the B&E research group [23]. This protocol is applied when a new instrumented glove is acquired, or after a repair of a glove. It consists in a set of recordings of controlled postures or movements, in order to obtain the coefficients that correlate joint angles with gauge signals by means of regressions. This protocol was adapted for the 22 DoF gloves acquired later, by adding some static postures with controlled DIP angles.

From previous experience, B&E researchers were already aware of some problems of the gloves, as the necessity of using a Velcro strap around the wrist to compensate the poor fitting of the two gauges measuring wrist flexion and abduction. A thorough knowledge of all those problems that may arise from the use of the instrumented gloves is key before planning the main experiments of the thesis. Thus, this chapter goes across all the experiments carried out in this sense.

One of the main concerns was the effect on hand kinematics of wearing instrumented gloves during product manipulation. As the proverb says, "A cat with gloves catches no mice", and some works reported in literature that using work gloves reduces manual skills, testing butyl rubber gloves [170], cotton jersey gloves with protective material zones [171], special gloves for extra vehicular activities in space [172] or comparing between a glove made of cotton, another made of nylon and another made of cotton with nitrile [173]. If this reduction is considerable, it can lead to perform other movements or grasps than the ones performed in bare-handed conditions, therefore affecting hand kinematics. Thus, a study was conducted in order to evaluate the effect of wearing instrumented gloves on manual skills, tested during the performance of hand functional tests requiring different levels of manipulation precision. The evaluation was performed through comparison of functional test scores and times of accomplishment while wearing instrumented gloves and in bare-handed conditions.

Selecting the most appropriate glove model (18 DoF or 22 DoF) to perform the experiments was also a decision that required a previous testing process. The size of the 22 DoF gloves is slightly larger than the 18 DoF ones in order to locate the extra gauges to measure DIP joints (see section 3.3), and some fit problems were experienced for some subjects' hands. Therefore, a study regarding the suitability of using the 22 DoF gloves to measure DIP joints was also carried out. Nevertheless, previous observations from literature regarding possible correlations between PIP and DIP joints [174]–[178] might be used to estimate DIP joint kinematics from PIP ones in those subjects who had fit problems with the 22 DoF gloves. However, the majority of those studies were performed in free motion conditions [174]–[177], and those studying manipulation [178] were limited to grasping cylinders. Therefore, the next study presented consisted in studying possible correlations between PIP and DIP joints kinematics during manipulation of objects in activities of daily living.

In addition, performing activities of daily living requires reaching products, manipulating them, and finally releasing them. Therefore, distinguishing between these three phases is key when studying hand kinematics. This distinction could be manually done through visual analysis, or it can be automated by means of using pressure sensors. In an attempt to automate such distinction, and as the CyberGlove does not have pressure sensors, a commercially available glove with pressure sensors was tested. Therefore, the last study presented in this chapter consists in a comparison between the CyberGlove and the Virtual Motion Glove 30 (Virtual Motion Labs, TX, USA), which was acquired by the B&E research group and tailored with extra pressure sensors. This comparison considered their accuracy for hand kinematics measurement and for distinguishing the different recording phases (performed with visual analysis in the CyberGlove and with pressure sensors in the Virtual Motion Glove 30).

Conclusions drawn from all these studies contributed to better interpret the results from all the experiments throughout the thesis. This information will be key when planning future experiments, so as to bear in mind important considerations regarding gloves' functioning. All these considerations were thought to be useful information for all those researchers planning similar experiments. For this reason, the study regarding the effect on manipulation skills was published in the Journal of Biomechanics, and the other experiments were presented in international conferences, in order to give advice to all those researchers interested in using instrumented gloves.

3.2 Effect on manual skills of wearing instrumented gloves

The work presented in this section was published in Journal of Biomechanics as a Brief Report under the title "Effect on manual skills of wearing instrumented gloves during manipulation" [179].

3.2.1 Introduction

Instrumented gloves are motion capture systems widely used due to the setup simplicity and the absence of occlusions when manipulating objects (common drawback in optical systems). They have been applied for different purposes in biomechanics: in hand kinematics applied for patients' functional assessments [157], [180], sign language recognition [181], precision gesture control in surgery [182], [183], simulation [184], [185], validating other motion data systems [186], [187], and for characterising hand dynamics combined with EMG recording [36], [188], [189]. Some of these applications only use joint angles, while others also consider joint velocity and acceleration. The analysed tasks covered a wide range of activities with different manipulation precisions, from fine to gross manipulation, and also non-manipulative activities. Nevertheless, work gloves affect grasping and manipulation capabilities, which leads us to wonder about the effect of using instrumented gloves on manual skills such as CyberGlove (CyberGlove Systems, San Jose, CA, USA), the most widely used in biomechanics [101], [190], [191].

In order to evaluate work gloves' effects on dexterity, some studies propose indicators such as the index of dexterity in manipulation (using O'Connor and Purdue Pegboard tests [170], [192], [193] or other non-standardised tasks such as pegboard tasks, block manipulation, rope knotting or assembly tasks [171], [172]), touch sensitivity using the Semmes-Weinstein monofilament test set [173], [194], grip strength [171], [173], [194]–[196] or range of motion [197]. These studies show that using work gloves reduces dexterity [170]–[173]. Such reductions vary from a slight decrease in dexterity test scores [198] to increases of up to 87% in the time of accomplishment of the test [196], depending on the glove characteristics. Dexterity reduction depends on the glove material and thickness [171], [193], [199], [200], and is greater for stiff and bulky materials such as leather [196] than for thinner materials such as latex [198].

Given the effects of using work gloves reported in literature, the aim of this work is to quantify the effect of using a CyberGlove on manual skills when performing tasks requiring different degrees of precision, which is still unknown. This will help establishing the limitations of using the glove in biomechanics, especially in research applications where specific kinematic parameters are quantified. The analysis was performed using three different standardised tests: the Box & Block Test (BBT), which evaluates gross motor skills; the Purdue Pegboard Test (PPT), which evaluates fine motor skills, and the Sollerman Hand Function Test (SHFT), which focuses on the capability to perform activities of daily living (ADLs).

3.2.2 Methods

Subjects

Thirty healthy adult subjects (16 male, 14 female; 37.83±8.07 years of age) participated in the experiment, approved by the University ethics committee, after signing their written informed consent. Subjects' laterality (27 right-handed and 3 left-handed) was determined using the Edinburgh Handedness Inventory [201].

3.2.3 Material

One left- and one right-hand CyberGlove were used, together with the kits for the three standardised tests (Figure 3.2.2): BBT [80] to evaluate gross motor skills, PPT [81] to fine motor skills and SHFT [82], which evaluates the capability to perform ADLs. CyberGlove is made of a synthetic elastic mesh fabric on the palm side, and a denser synthetic elastic fabric on the back in which the 18 resistive bend-sensors and the wiring are embedded. Following the manufacturer's instructions, a thin nylon inner glove is worn to keep the CyberGlove clean and in good condition. The tips of the fingers are covered only by the inner glove (Figure 3.2.1). The CyberGlove is worn and secured with a Velcro strap around the wrist. An elastic band around the wrist, commonly used during recordings, was used to ensure a better fit of the wrist sensors.

Note that gloves were not acquiring data during the tests, as our aim was to compare just the scores of the dexterity tests while wearing gloves and bare-handed.

Figure 3.2.1: Dorsal and palmar views of the CyberGlove instrumented glove used in the experiments.

3.2.4 Experiments

Each subject performed the three tests twice (bare-handed and wearing the gloves on both hands), the order being randomised for each participant. The experiment was divided into two sessions, in order to prevent subjects from getting tired. Thus, the BBT and PPT tests were conducted in the first session and the SHFT during the second session. Each test was performed following its standardised instructions. The BBT (Figure 3.2.2a) comprises one trial for each hand, in which the subject has to pass wooden blocks from one box to another within 60 seconds [80]. The PPT (Figure 3.2.2b) comprises four trials: the first three trials consist in putting pins into holes on a board within 60 seconds (with the right hand, the left hand and simultaneously with both hands), and the fourth consists in assembling pins and washers with both hands [81]. The SHFT (Figure 3.2.2c and Figure 3.2.2d) involves performing 20 tasks that are representative of ADLs, following the operator's instructions, which include whether subjects have to use both hands or only the dominant one [82]. The subjects were asked to perform all the tests at the maximum possible pace, but abiding by the test rules.

Figure 3.2.2: The different tests performed in the experiment. (a) Box & Block Test, (b) Purdue Pegboard Test, (c, d) Sollerman Hand Function Test.

3.2.5 Data analysis

Results from the tests were measured according to their standardised scorings:

- BBT: blocks passed in each trial.
- PPT: pieces assembled in each trial.
- SHFT: each task is assigned a five-level score according to the type of grasp used, the level of difficulty observed and the time of accomplishment of the task (4 when the accomplishment is as expected, 0 when the task is not performed). A global score is computed as the sum of these 20 scores.

The reductions in scores due to the instrumented gloves were computed for each subject and trial. Descriptive statistics are presented. Seven repeated-measures ANOVAs were performed on the scores of each BBT and PPT test, and on the global score of the SHFT. In all cases, the factor was the use of gloves, to determine its effect on the manual skills assessed by each test. The dependent variables in the seven ANOVAs were BBT score with right hand, BBT score with left hand, PPT score with right hand, PPT score with left hand, PPT with both hands and SHFT global score.

Furthermore, a detailed analysis of the SHFT tasks was performed through their individual scores and times of accomplishment. Twenty repeated-measure ANOVAs, one for each task, were performed on scores and times as dependent variables, again with the use of gloves as the factor. Moreover, score variation and time increase percentages when using gloves were computed for each task.

3.2.6 Results

Table 3.2.1 presents the descriptive statistics (mean and standard deviation) of the scores and their reductions for BBT, PPT and SHFT trials. Significant differences from the ANOVAs are marked. As expected, scores when wearing gloves are lower than those achieved without them. The seven ANOVAs for the test scores were significant (bilateral asymptotic significance ≤0.01), showing that the use of gloves affects all types of dexterity analysed.

Table 3.2.1: Mean (SD) scores and mean (SD) reduction of scores obtained for BBT, PPT and SHFT. Tests "PPT Both 1" when putting the pins in the pegboard with both hands simultaneously, and "PPT Both 2" when performing the assembly task (both hands). Tests with significant differences (sig.≤0.01) in the repeated measures ANOVAs have been marked (**).

Test	Score without glove	Score with glove	Score reduction (%)
BBT Right**	80.23 (8.46)	74.23 (9.55)	7.32 (9.73)
BBT Left**	76.77 (7.24)	70.27 (7.56)	8.37 (6.30)
PPT Right**	16.93 (2.16)	12.73 (2.16)	24.47 (11.17)
PPT Left**	15.17 (2.00)	11.73 (1.89)	22.16 (11.91)
PPT Both 1**	25.40 (3.33)	18.20 (3.69)	27.75 (14.91)
PPT Both 2**	44.13 (6.86)	25.57 (8.34)	41.76 (18.72)
SHFT**	74.07 (1.70)	72.07 (2.13)	2.68 (2.79)

Table 3.2.2 presents the descriptive statistics for the individual scores of the SHFT tasks. Significant differences from the ANOVAs are marked. All the tasks with significant differences presented a decrease in scores when performed with gloves.

Table 3.2.2: Mean (SD) scores obtained in each SHFT task and percentage of score difference (negative values for decrease in dexterity with gloves). Tasks with significant differences (sig.≤0.01) in the repeated measures ANOVAs have been marked (**).

ID	Task	Score without glove	Score with glove	Score difference (%)
1	Pick up coins from flat surface, put into a purse mounted on wall	4.00 (0.00)	3.87 (0.43)	-3.33 (10.85)
2	Open/close zip	4.00 (0.00)	4.00 (0.00)	0.00 (0.00)
3	Pick up coins from purses**	3.93 (0.25)	3.37 (0.67)	-13.89 (18.87)
4	Lift wooden cubes over edge 5cm in height	4.00 (0.00)	4.00 (0.00)	0.00 (0.00)
5	Lift iron over edge 5cm in height	3.93 (0.36)	3.93 (0.36)	+1.67 (20.69)
6	Turning screw with screwdriver	3.87 (0.51)	4.00 (0.00)	+6.66 (25.37)
7	Pick up nuts and screw on bolts**	3.47 (0.51)	2.90 (0.61)	-15.00 (21.37)
8	Put key into lock, turn 90 degrees	4.00 (0.00)	4.00 (0.00)	0.00 (0.00)
9	Turn door-handle 30º	3.93 (0.36)	4.00 (0.00)	+3.33 (18.25)
10	Unscrew lid of jars	2.73 (0.98)	2.87 (1.01)	+8.33 (32.38)
11	Do up buttons**	3.90 (0.30)	3.37 (0.49)	-13.05 (15.11)
12	Put on tubigrip stocking on the other hand	4.00 (0.00)	3.93 (0.25)	-1.67 (6.34)
13	Cut play dough with knife and fork	4.00 (0.00)	3.97 (0.18)	-0.83 (4.56)
14	Write with a pen	4.00 (0.00)	4.00 (0.00)	0.00 (0.00)
15	Fold sheet of paper and put into envelope**	3.80 (0.41)	3.13 (0.57)	-16.67 (17.51)
16	Put a paper-clip on an envelope	4.00 (0.00)	4.00 (0.00)	0.00 (0.00)
17	Lift telephone receiver, put to ear	3.93 (0.36)	4.00 (0.00)	+3.33 (18.26)
18	Pour water from carton	2.10 (0.40)	2.13 (0.43)	+3.33 (22.49)
19	Pour water from jug	4.00 (0.00)	4.00 (0.00)	0.00 (0.00)
20	Pour water from cup	2.47 (0.86)	2.60 (1.07)	+10.00 (46.23)

Table 3.2.3 shows the detailed analysis for the time of accomplishment of each SHFT task. Again, significant differences in the ANOVAs are marked. When wearing gloves, times were higher in all the tasks and significant differences were found in all the tasks except two.

Table 3.2.3: Mean (SD) time of accomplishment (in seconds) of each SHFT task and mean (SD) percentage of time increase. Significant differences after applying a repeated measures ANOVA were marked ((*) when sig.≤0.05, (**) when sig.≤0.01).

ID	Task	Time of accomplishment without glove (sec)	Time of accomplishment with glove (sec)	Time increase (%)
1	Pick up coins from flat surface, put into a purse mounted on wall**	7.20 (1.69)	13.40 (8.14)	101.51 (163.75)
2	Open/close zip**	7.27 (1.74)	8.60 (1.96)	20.74 (23.55)
3	Pick up coins from purses**	14.50 (3.67)	23.70 (9.79)	69.54 (66.55)
4	Lift wooden cubes over edge 5cm in height**	4.13 (1.01)	4.90 (0.84)	23.47 (28.04)
5	Lift iron over edge 5cm in height**	3.43 (0.94)	3.93 (0.78)	20.67 (34.58)
6	Turning screw with screwdriver**	7.47 (1.85)	9.57 (2.46)	33.92 (41.48)
7	Pick up nuts and screw on bolts**	22.87 (6.36)	33.10 (12.91)	49.58 (53.12)
8	Put key into lock, turn 90 degrees**	4.87 (1.14)	7.27 (1.84)	53.28 (37.51)
9	Turn door-handle 30º*	2.73 (0.58)	3.07 (0.69)	15.28 (30.96)
10	Unscrew lid of jars**	6.80 (1.61)	8.27 (2.12)	24.41 (28.70)
11	Do up buttons**	15.13 (4.0)	22.50 (6.13)	53.94 (45.13)
12	Put on tubigrip stocking on the other hand**	8.03 (2.16)	12.67 (4.21)	65.54 (63.09)
13	Cut play dough with knife and fork	10.47 (3.42)	11.33 (3.00)	13.22 (26.68)
14	Write with a pen**	5.40 (1.10)	6.47 (1.31)	21.18 (17.90)
15	Fold sheet of paper and put into envelope**	16.63 (4.33)	22.33 (4.37)	40.42 (35.80)
16	Put a paper-clip on an envelope**	5.33 (1.32)	7.57 (1.99)	50.10 (52.14)
17	Lift telephone receiver, put to ear**	2.00 (0.37)	2.63 (0.81)	37.22 (53.19)
18	Pour water from carton**	19.83 (2.39)	21.23 (3.05)	7.19 (9.66)
19	Pour water from jug*	7.40 (2.14)	7.97 (1.90)	11.11 (23.53)
20	Pour water from cup	6.00 (1.51)	6.43 (1.30)	10.92 (24.42)

Figure 3.2.3 shows an overview of the percentage of score reduction observed for BBT, PPT and SHFT (Table 3.2.1), along with the mean percentage of reduction of scores of SHFT tasks (Table 3.2.2) and the mean percentage of increase in time of accomplishment of SHFT tasks (Table 3.2.3).

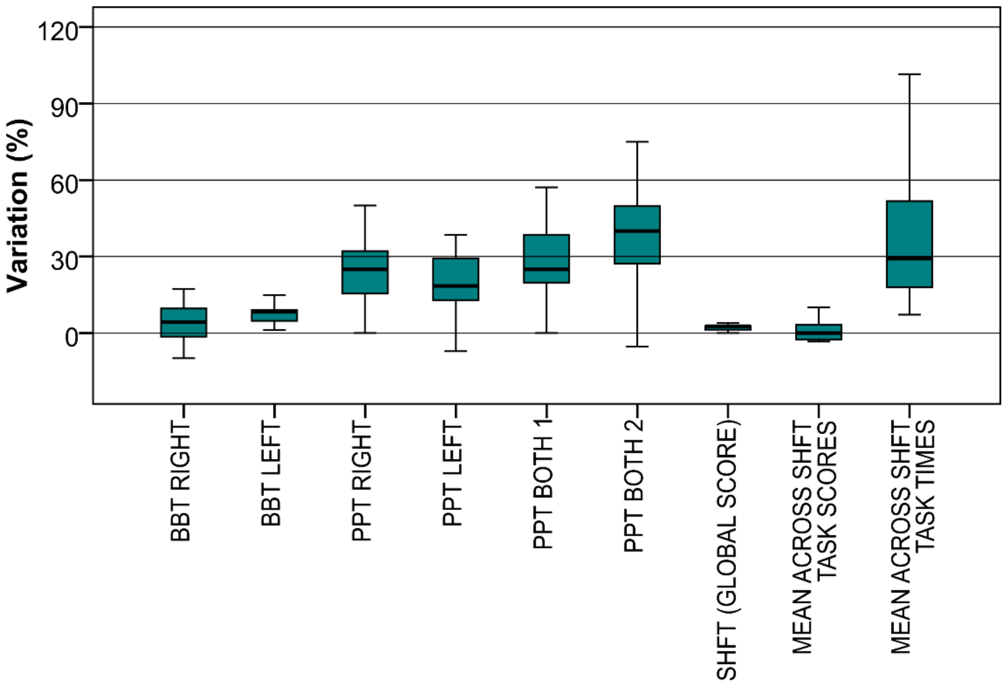


Figure 3.2.3: Changes in scores and mean time.

3.2.7 Discussion

In accordance with previous works [170]–[173], [196], [198], the scores when using gloves showed a reduction in motor skills and manipulation capabilities at different levels of precision. This reduction has been previously reported to depend on certain glove characteristics like glove material and thickness [171], [193], [199], [200]. Furthermore, wearing a glove implies a change in frictional conditions which, depending on the glove's material, affects manipulation to different extents [202], [203]. With the CyberGlove model with 18 DoF, which has uncovered fingertips, the protective inner glove is worn (as indicated by the glove manufacturer), which reduces touch sensitivity. For this glove model, cutting the finger ends of the inner glove to uncover fingertips may help increase touch sensitivity and, therefore, dexterity.

Fine motor skills, evaluated through the PPT, are highly affected by the use of instrumented gloves, as shown by a reduction in the scores by 29% (mean reduction of the four parts of the test). The highest reductions were found in the parts of the PPT that required the use of both hands simultaneously, i.e. the ones involving the finest motor skills. The stronger effect on dexterity reported while performing precision tasks using both hands can be attributed to reduced somatosensory feedback in both hands simultaneously, which is highly related to touch of sensitivity which, in turn, diminishes while wearing gloves [173]. Such reduced feedback may affect manipulation [204] and, therefore, dexterity.

Gross motor skills, assessed by means of the BBT, are less affected, with a decrease of about 7.8%. The overall capability to perform ADLs, when assessed through the standardised score of the SHFT, is only affected by a reduction of 2.7%. The difference in the individual scores for each task varies from a reduction of 16.67% to an increase of 10%, which is statistically significant only in the four tasks that involve the finest motor skills (picking up coins, screwing nuts, buttoning and unbuttoning, and folding paper and putting it into an envelope) where the score decreases.

However, the standardised score for the SHFT is quite rough, and especially the individual scores, which only consider a five-level score and the time of accomplishment of the tasks is considered in wide ranges (<20s, <40s, <60s, >60s). Furthermore, the grasp classification score may be somewhat subjective, as it depends on the operator. Nevertheless, when considering the exact times of accomplishment, increases from 7% to more than 100% were found, most of them statistically significant, even though no important reductions were found in the SHFT scores. The SHFT contemplates a large number of representative tasks and grasps (in comparison to BBT and PPT), but it was designed to evaluate patients with an important reduction in mobility (e.g. after an ictus). Hence despite its validity having been proved with patients with chronic stroke [205] or burned hands [206] to measure hand function, it is not accurate enough to measure the effects of wearing gloves.

With regard to the effects on hand kinematics, the only information that can be extracted from BBT and PPT is that the decrease in scores reported implies a lower velocity of performance, and therefore lower hand joint velocity can be expected. The same occurs with the times of accomplishment reported in SHFT. Nevertheless, the stiffness of the glove may be affecting the range of motion and, consequently, hand kinematics. We can therefore observe that kinematic parameters (i.e. velocities and postures) may be affected when wearing instrumented gloves. Thus, data obtained using other motion capture systems that do not affect motor skills (e.g. optical systems) should not be compared with those obtained using instrumented gloves, in order to avoid bias.

A possible bias in studies that have used data gloves can be discussed from the results obtained herein depending on the recorded tasks and the reported parameters. Applications that have used the glove to record grasping static postures to validate other motion data systems [186], [187] or simulation [184], [185] would not be affected by reported loss of dexterity, although the analysed postures may slightly differ from those used in bare-handed conditions [207]. Similarly, applications that have recorded free movements for purposes such as identifying the intended type of grasp or movement performed [36], [157], [189] would not be significantly affected by loss of dexterity, although glove stiffness may require slightly higher muscle activity to perform the movements. On the contrary, applications in high precision tasks, such as assessing manual dexterity in simulation-based surgery [182], [183], would be clearly affected. Therefore, existing gloves should be improved for such purposes. In addition, the studies that have analysed joint velocities and/or accelerations [181], [188], [208] may report lower velocities than real ones as the time required to perform a task would be longer than for doing it bare-handed. The joint velocity bias is expected to be higher for those tasks requiring more precision. Nevertheless, dexterity may also be affected when recording hand posture by other motion capture systems (e.g. markers of optical motion capture systems that may collide during manipulation), and this effect has not yet been studied as far as the authors know.

Even though, despite all the advantages that instrumented gloves offer regarding other motion capture systems, it is not the most suitable motion capture system when performing tasks requiring fine motor skills (as the laparoscopy in Sánchez-Margallo et al., 2014), but are appropriate for gross motor skills and activities of daily living (as in Gracia-Ibáñez et al., 2017). However, users should take into account that kinematic parameters such as velocities should not be compared with those obtained using other systems.

3.2.8 Conclusions

The use of instrumented gloves to record hand kinematics is only recommended when performing tasks requiring medium and gross motor skills. Care has to be taken when comparing velocities with those obtained using other systems.

3.3 Problems of using instrumented gloves to measure distal interphalangeal joints

An abstract of this section was presented in the 25th Congress of European Society of Biomechanics (2019) under the title "Suitability of using instrumented gloves to measure distal interphalangeal joints kinematics".

3.3.1 Introduction

As presented in section 2.2.2, instrumented gloves are a motion capture system widely used when studying hand kinematics [18], and the most commonly implemented technology on those gloves is the measurement using strain gauges. Each of those gauges has its specific location in the glove in order to measure the rotation in a different degree of freedom (DoF). Nevertheless, some commercially available instrumented gloves are equipped with more gauges than others. An example of this are the CyberGlove gloves. As mentioned previously, there is a model that allows measuring 18 DoF (from wrist, thumb carpometacarpal, palmar arch, metacarpophalangeal and proximal interphalangeal joints (PIP), which was the model used in the experiment presented in section 3.2) and another that allows measuring 22 DoF, which allows also recording the distal interphalangeal joints (DIP). Thus, in order to locate these extra gauges, the fingers of this glove model are slightly longer to accommodate big hands, which may introduce problems related to improper fit of the glove depending on the hand size. Therefore, the aim of this work is reporting the problems faced in the B&E research group when using the 22-DoF Cyberglove: during the first testing recordings performed when it was acquired, during the calibration procedure of the glove according to the protocol presented in [23], and during the use of the glove, once calibrated, in an experiment to characterise hand kinematics, which consisted in recordings of subjects performing a standardised hand function test. The main purpose of this section is giving a piece of advice to future instrumented glove users/manufacturers.

3.3.2 Methods

Experiments were performed in three different phases, which consisted in the initial testing of the gloves when acquired (Phase I), calibration of the glove gauges (Phase II) and recording of subjects performing a standardised hand function test (Phase III). A right and a left instrumented gloves, CyberGlove III, with 22 DoF, were used to acquire data in all the phases of the experiment. All the experiments were approved by the University ethics committee and all the subjects were previously informed about the characteristics of the experiment and gave their written consent.

Phase I

Phase I of the experiment consisted in the initial testing of gloves when acquired. Six healthy adult subjects (3 male, 3 female; 5 right-handed and 1 left-handed, hand length from 172 to 196 mm) volunteered to participate in the experiment. Firstly, in order to ensure that all the gauges were actively recording, free movement and grasping a computer mouse and a pen (both performed with their dominant hand) were recorded. After this, controlled flexion of PIP and DIP joints was also recorded, by using wooden pieces of 35º and 75º (Figure 3.3.1). In order to control flexion, pressure was applied both in palmar and dorsum sides of the finger, as observed in Figure 3.3.1. When recording the PIP joint of a finger, the DIP of the same finger was controlled to have no flexion, and vice versa. Recordings were performed from index to little finger in both hands.

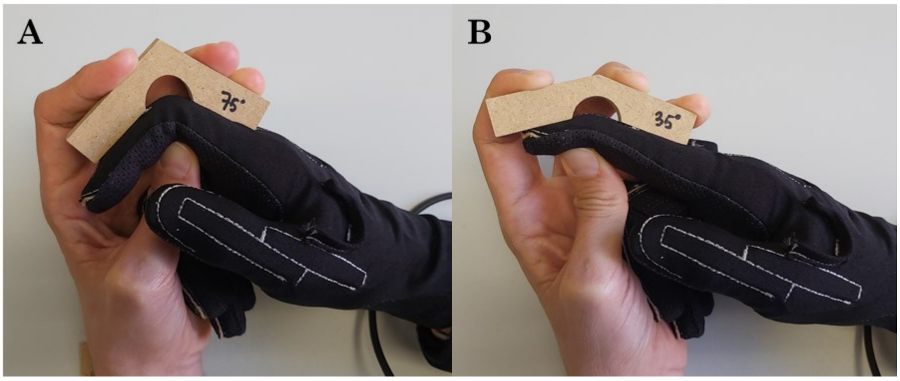


Figure 3.3.1: Controlled static postures recorded using wooden pieces.

Phase II

Experiment Phase II consisted in the calibration of the gauges of both gloves (right and left). Ten healthy adult subjects (male, 8 right-handed and 2 left-handed, hand length from 184 to 207 mm) volunteered to participate in the experiment. Minimum hand length required to participate was 184mm, as the minimum recommendable hand length for using the 22 DoF CyberGlove was observed to be about 184 mm after performing Phase I experiments, and it was used to select subjects for Phases II and III. The calibration was performed taking as reference the protocol for 18 DoF CyberGlove proposed in [23] (Appendix I), but adding some recordings in order to calibrate the gauges of the DIP joints.

The recordings proposed in the original protocol consisted of controlled static postures (using wooden pieces and other materials specified in detail in the original article [23]), as well as controlled movements. These recordings allowed computing the gains of each gauge by means of linear regressions or optimization processes, depending on the gauge. The protocol also considered cross coupling existing between some gauges (e.g., gauges measuring flexion and abduction at metacarpophalangeal joints).

Nevertheless, in order to calibrate the 22DoF CyberGlove it was necessary to add eight additional recordings to the original protocol. Those postures consisted in static postures of the four distal interphalangeal joints with flexion of 0º and 75º, in order to obtain the gains by means of linear regressions.

Phase III

The experiment corresponding to Phase III was performed on the same subjects that were recruited in Phase II. Those subjects performed the complete Sollerman Hand Function Test while wearing the instrumented gloves on both hands (Figure 3.3.2). As detailed in section 3.2, this hand function test consists of 20 tasks considered representative of the activities of daily living (Table 3.2.2). They were asked to perform the tasks using their dominant hand or, in some occasions, both hands (Table 3.2.2). A description of the tasks and material to perform each one is given in the original article presenting the test [82].

Figure 3.3.2: Subject performing the Sollerman Hand Function Test while wearing the 22 DoF CyberGloves.

3.3.3 Results and discussion

Phase I

Several problems were reported during the performance of the different phases of the experiment. Extreme (non-natural) flexion/extension values were recorded during the grasping tasks recorded, in small and medium-sized hands (length under 184mm). After inspection, it was checked that these values were attributable to the bad fitting of the glove to the hand, so that it bends when it contacts with an object or surface (Figure 3.3.3a).

Furthermore, flexion at PIP or DIP joints was recorded during the controlled flexion trials, when the joints were not actually flexed. This effect occurred because gauges are too large and span both PIP and DIP joints (they physically overlap on the glove), thus recording cumulative flexion of adjacent joints (Figure 3.3.3b).

The minimum recommendable hand length for using the 22 DoF CyberGlove was established about 184 mm, determined as the minimum hand size among all the subjects that did not present extreme values during the experiments. This size corresponds to a 33 percentile of men and a 90 percentile of women, and it was used to select subjects for Phases II and III. Nevertheless, no fitting problems were observed related with subjects' hand width, as the elastic fabric of the main body of CyberGlove allows a tighten fitting to the palm.

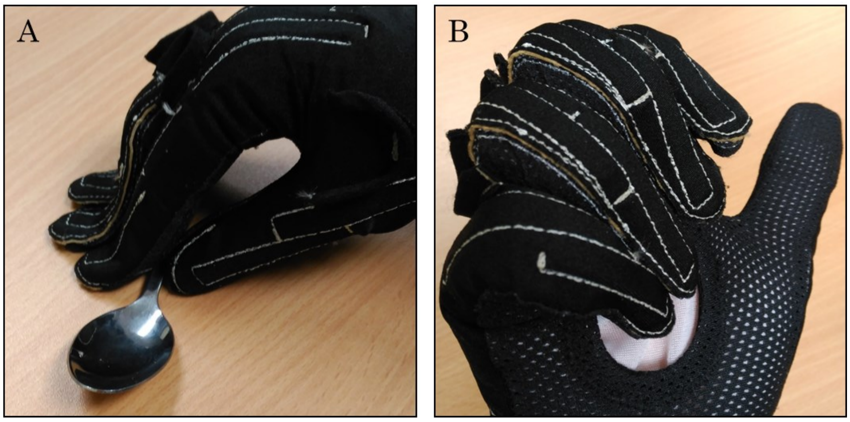


Figure 3.3.3: a) Fingertips hindering manipulation and bending. b) PIPs sensors spanning on PIPs and DIPs.

Phase II

Controlled flexions of DIP joints under 35° during the calibration protocol recordings provided no change in the signal from the gauges in more than 50% of occasions. Again, these situations evidenced more fitting problems, in this case because of too thin fingers, so that the finger moved within the glove without bending the gauges (Figure 3.3.4).

Figure 3.3.4. Middle finger DIP flexed without bending the corresponding gauge.

Phase III

Subjects reported a lack of touch sensitivity while performing the Sollerman Hand Function Test, which is obviously attributable to the fact that fingertips are covered with glove (contrarily to the 18 DoF glove) (Figure 3.3.5).

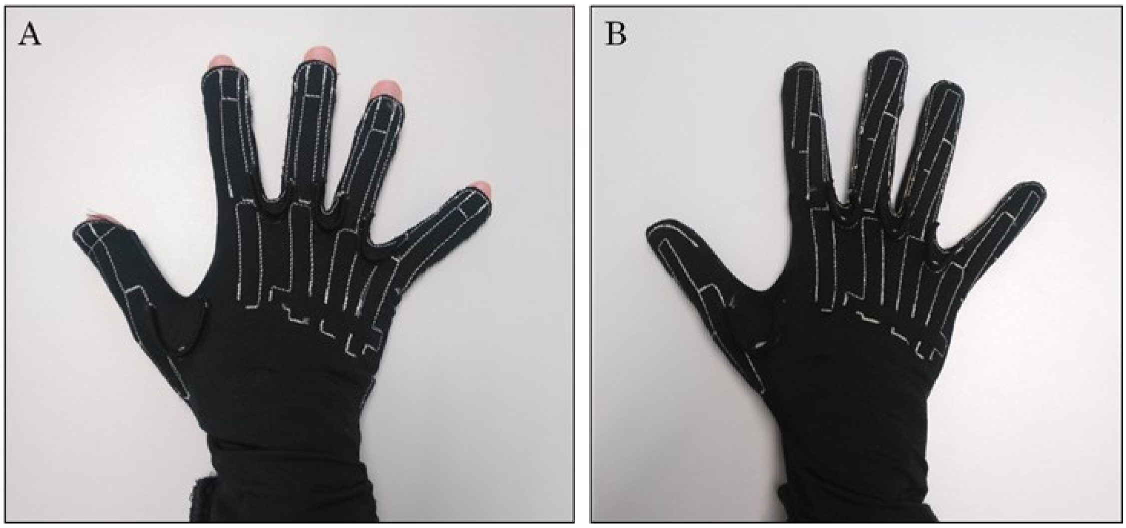


Figure 3.3.5: Differences on fingertip covering between 18 DoF CyberGlove (A) and 22 DoF CyberGlove (B).

Apart from this, the mean functional range of motion (FROM) of DIP across all the subjects (Table 3.3.1) was calculated as the percentiles 5 and 95 of recorded joint angles (see boxplot of the angles recorded for each subject in Figure 3.3.6). The FROM for DIP joints was found to be lower than that reported from literature [137], obtained with manual recording. This reduction can be attributable to the excessive tightness of the glove, reducing mobility, as well as to the fitting problems reported in Phase II in thin fingers.

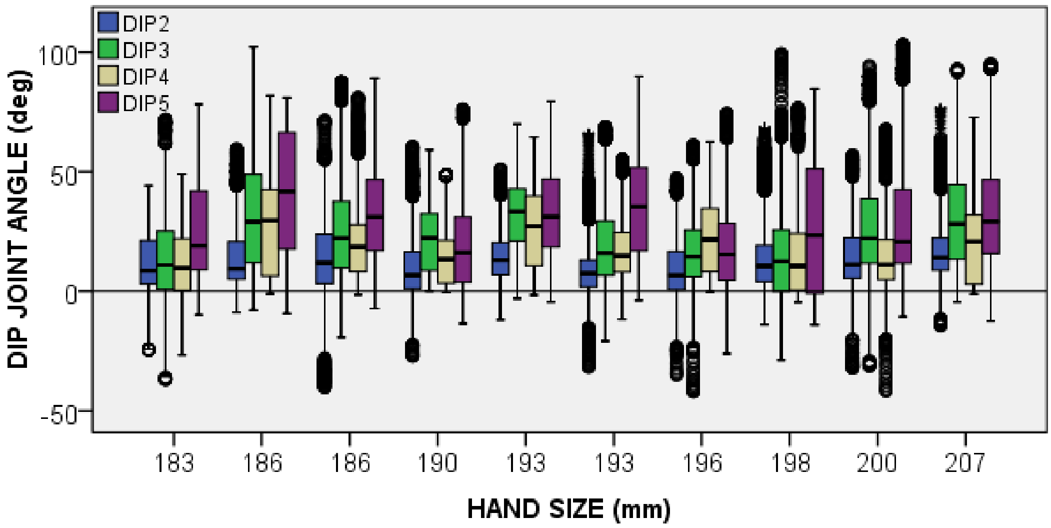


Figure 3.3.6: Recorded DIP angles for each subject and finger. Each subject has been labelled with his/her hand size (in mm).

Table 3.3.1: Recorded DIP joints FROM during Sollerman Hand Function Test (SHFT).

Joint	Recorded FROM during SHFT (P5/P95) (deg)
Index DIP	-4.15 / 38.35
Middle DIP	-1.71 / 61.24
Ring DIP	-0.48 / 50.26
Little DIP	-1.34 / 78.38

3.3.4 Conclusions

From our experience, more information regarding the glove sizing is needed when acquiring an instrumented glove with sensors to measure DIP joints. A big-sized one, as the CyberGlove 22-DoF, should not be used to study the kinematics of a sample of subjects intended to be representative of adult population regarding hand sizes and gender. Usability of instrumented gloves could be significantly improved if two or three different glove sizes were commercially available, or if position/size of gauges was reconsidered during design or during use and if thinner materials were used to tailor the main body of the glove.

3.4 Relationship between proximal and distal interphalangeal joint angles

The work presented in this section is being prepared to be submitted to the international journal Human Movement Science.

3.4.1 Introduction

As seen in previous sections, DIP joints cannot be measured in small and medium sized hands using the CyberGlove. Alternatively, estimating DIP joint angles could be considered by taking profit of the kinematic linkage existing between PIP and DIP joints, which has been attributed to fingers' tendinous system and ligaments [210], [211]. Several works have studied and quantified this linkage. Table 3.4.1 summarizes main experimental regression values reported in literature. Most of the studies were limited to the analysis of free motion (opening and closing the fist) [174]–[177]. The study of the PIP and DIP linkage during grasp or manipulation has been limited to grasping cylinders with different diameter [178], and revealed that the regressions were different for different fingers, but consistent independently of the cylinder diameter.

All the regressions presented in Table 3.4.1 assumed zero offset except the one presented by Kim et al. [176], where the experimental offset observed was negligible (<1deg.). Slopes observed are quite similar in all the works, being those obtained during free motion higher for index finger, followed by middle, ring and little [176], [177], in contrast to the slopes observed during grasping conditions [178]. Consequently, it is hypothesised that the measuring conditions may affect the slope values. Therefore, this work proposes studying the linkage between DIP and PIP joints while performing activities of daily living (ADLs), using different products and performing different grasp types, and delimiting the error arisen when estimating DIP joint angles in ADLs from PIP ones using the slopes observed during free motion.

Table 3.4.1: Regressions of interphalangeal joints angles obtained in literature with DIP angle (θDIP) as dependent variable and PIP angle (θPIP) as independent.

AUTHORS	TASK/FINGERS ANALYSED	MOTION CAPTURE SYSTEM	REGRESSIONS OBTAINED (angles in deg.)
Hahn et al. [174]	Opening-closing the fist / Both index fingers	Ultrasound marker system	Index: $\theta_{DIP} = 0.76 \cdot \theta_{PIP}$
Van Zwieten et al. [175]	Theoretical model validated with opening-closing the fist		S-shape curves with parameters dependent of subject's anatomy, generic for index to little fingers. Mean slope in central linear zone ≈ 0.75
Kim et al. [176]	Opening-closing the fist / Right hand fingers	CyberGlove instrumented glove	Index: $\theta_{DIP} = 0.6175 \cdot \theta_{PIP} + 0.4199$ Middle: $\theta_{DIP} = 0.4715 \cdot \theta_{PIP} + 0.7023$ Ring: $\theta_{DIP} = 0.4390 \cdot \theta_{PIP} + 0.7336$ Little: $\theta_{DIP} = 0.4143 \cdot \theta_{PIP} + 0.5665$
Mentzel et al. [177]	Opening-closing the fist / Right hand fingers	Customised instrumented glove	Index: $\theta_{DIP} = 0.77 \cdot \theta_{PIP}$ Middle: $\theta_{DIP} = 0.75 \cdot \theta_{PIP}$ Ring: $\theta_{DIP} = 0.75 \cdot \theta_{PIP}$ Little: $\theta_{DIP} = 0.57 \cdot \theta_{PIP}$
Gülke et al. [178]	Grasping cylinders of different diameter / Right hand fingers	Customised instrumented glove	Index: $\theta_{DIP} = 0.632 \cdot \theta_{PIP}$ Middle: $\theta_{DIP} = 0.682 \cdot \theta_{PIP}$ Ring: $\theta_{DIP} = 0.984 \cdot \theta_{PIP}$ Little: $\theta_{DIP} = 0.496 \cdot \theta_{PIP}$

3.4.2 Methods

Subjects

Nine healthy adult subjects volunteered to participate in the experiment, approved by the university ethics committee. Minimum hand length required for being recruited was 184 mm, attending to fitting problems presented by the instrumented gloves (oversized for small and medium hands), according to the minimum hand length established in section 3.3 for using the 22DoF CyberGlove. Thus, all the subjects were males (6 right-handed and 3 left-handed, aged 32.7±12.2 years), with mean hand length 192.9 mm (SD 7.8 mm). All the subjects were previously informed about the characteristics of the experiment and gave their written consent.

Material

One left-hand and one right-hand 22-sensor CyberGlove III (with their corresponding protective inner gloves) were used for the experiment, together with the objects required to perform the tasks that are detailed in the following section (Figure 3.4.1).

Experimental conditions

The PIP and DIP joint angles of the participants were recorded with the instrumented gloves in two different experimental conditions: (i) performance of tasks representative of ADLs, and (ii) performance of a free motion task (FMT). The order of performance of the ADLs or FMT experimental condition was randomized for each subject. These experimental conditions are detailed afterwards.

Tasks representative of ADLs

Table 3.4.2 shows the complete list of ADLs performed in the experiment. The tasks consisted of the 20 ADLs proposed in the Sollerman Hand Function Test (SHFT) [82] as representative of the activities performed by a healthy adult subject during daily life, and 6 additional ADLs in order to include the performance of grasp types underrepresented in the SHFT (intermediate, special pinch and non-prehensile) according to real frequency of grasps in ADLs [212]. All the subjects performed the tasks following operator's instructions, which included whether subjects had to use both hands or only the dominant one according to SHFT instructions [82] (see Table 3.4.2). Time stamps during the ADLs recordings were marked by the operator when the subject started and finished the contact with the manipulated objects.

Figure 3.4.1: Scenario and objects required to perform the set of ADLs.

Table 3.4.2: ADLs performed in the experiment. Marked with "x" when using both hands was allowed.

ID	Both hands	ADL
1		Picking up a coin from flat surface, putting into purse mounted on wall
2		Opening/closing zip
3		Picking up a coin from a purse
4		Lifting wooden cubes over edge 5cm in height
5		Lifting iron over edge 5cm in height
6		Turning screw with screwdriver
7		Picking up nuts and put on bolts
8		Putting key into lock, turn 90 degrees
9		Turning door-handle 30º
10	x	Tying a shoe
11		Unscrewing lid of jars
12	x	Doing up buttons
13		Putting tubigrip stocking on the other hand
14	x	Cutting play dough with knife and fork
15		Eating with a spoon
16		Writing with a pen
17	x	Folding a paper and putting into envelope
18	x	Putting a paper-clip on envelope
19	x	Writing with a keyboard
20		Lifting telephone receiver, put it to ear
21	x	Pouring water from carton
22	x	Pouring water from jug
23	x	Pouring water from cup
24	x	Putting toothpaste in toothbrush
25		Spraying the table
26		Cleaning the table with a tea towel

Free motion task

Subjects were asked to perform a free motion task (FMT) while wearing the instrumented glove on their dominant hand. The free motion task consisted of flexing and extending the DIP and PIP joints three times (Figure 3.4.2), but contrarily to the movement used in previous studies [174]–[177], the metacarpophalangeal (MCP) joint was kept in neutral position, so as to allow full DIP flexion range, which was impeded when also flexing MCP joint because of contact of fingertips with the palm.

Figure 3.4.2: Free flexion of PIP and DIP recorded.

Data analysis

A previously validated protocol [23] was used to calculate the angles at the PIP and DIP joints of fingers 2 to 5 of right and left hands from the data recorded by the CyberGloves, acquired at a frequency of 100 Hz. The angles were then low-pass filtered (2nd order Butterworth filter, cut-off frequency 5 Hz), and static initial and final data of all recordings were trimmed. The recordings of tasks representative of ADLs were split into manipulation phase (ADL_M) and reaching plus release phases (ADL_R), using the time stamps marked by the operator during the recordings.

In order to achieve an appropriate statistical power so as not to commit type II error (given the analyses planned to perform with the data collected), and also reducing data computing system required capacity, data for each task and phase were reduced to 10 samples equally distributed along the task time for both measuring conditions. Henceforth, unless otherwise specified, all analysis refer to these reduced sets of data throughout the text.

Linear regressions between PIP and DIP joint angles of each finger (with DIP angle as dependent variable and PIP angle as independent) were applied to the FMT data of each subject, in two different ways: assuming null constant coefficient in the regressions and considering non-null constant coefficients. Therefore, 36 slopes (9 subjects × 4 fingers) were obtained for each type of regressions. Also, analogue linear regressions were applied to the ADL_M data of the 26 ADLs altogether for each subject, with null constant and non-null constant coefficients. Then, mean regression coefficients across subjects in each regression type and measuring condition (FMT and ADL_M) were obtained for each finger. Coefficients obtained from FMT data were used to estimate DIP joint angles during FMT, and those obtained from ADL_M data were used to estimate them during ADL_M and ADL_R. For each set of data (FMT, ADL_M and ADL_R), mean absolute error across subjects when estimating angles using both regression types (null and non-null constant coefficient regression) was computed for each finger and task. These errors were compared in order to select the regression type that presented best data fitting. Then, descriptive analyses of the coefficients and R squared obtained in the selected regression are presented.

Scatter plots of the PIP and DIP angles collected during the 26 ADLs (all data, not only the 10 values per task and phase) were represented for each subject, finger and phase (ADL_M and ADL_R), along with the regression line of his/her FMT data, in order to compare each subject's PIP-DIP linkage during ADLs and that observed during FMT, depending on the phase.

After this, the mean regression coefficients across subjects obtained in each measuring condition (FMT and ADL_M) for each finger were used to estimate DIP joint angles during ADL_M and ADL_R phases in two different ways: (i) using the mean slopes obtained in the FMT regressions, and (ii) using the mean coefficients obtained in the ADL_M regressions. Then, differences between these estimated DIP angles and the recorded ones at each instant were computed and represented in box and whiskers plots, in order to check the goodness of estimating DIP joint angles from PIP ones in each phase (ADL_M and ADL_R) depending on the regression coefficients used (FMT vs ADL_M). The box and whiskers plots were represented differentiating by task, in order to check whether the error is more critical in certain tasks.

Significant differences between the estimated and the measured angles in each phase (ADL_M and ADL_R) when using the FMT vs ADL_M regression coefficients were checked by means of 52 repeated measures ANOVAs (26 tasks x 2 phases), with the measuring condition (FMT or ADL_M) as factor. Figure 3.4.3 presents a flowchart of the data analysis.

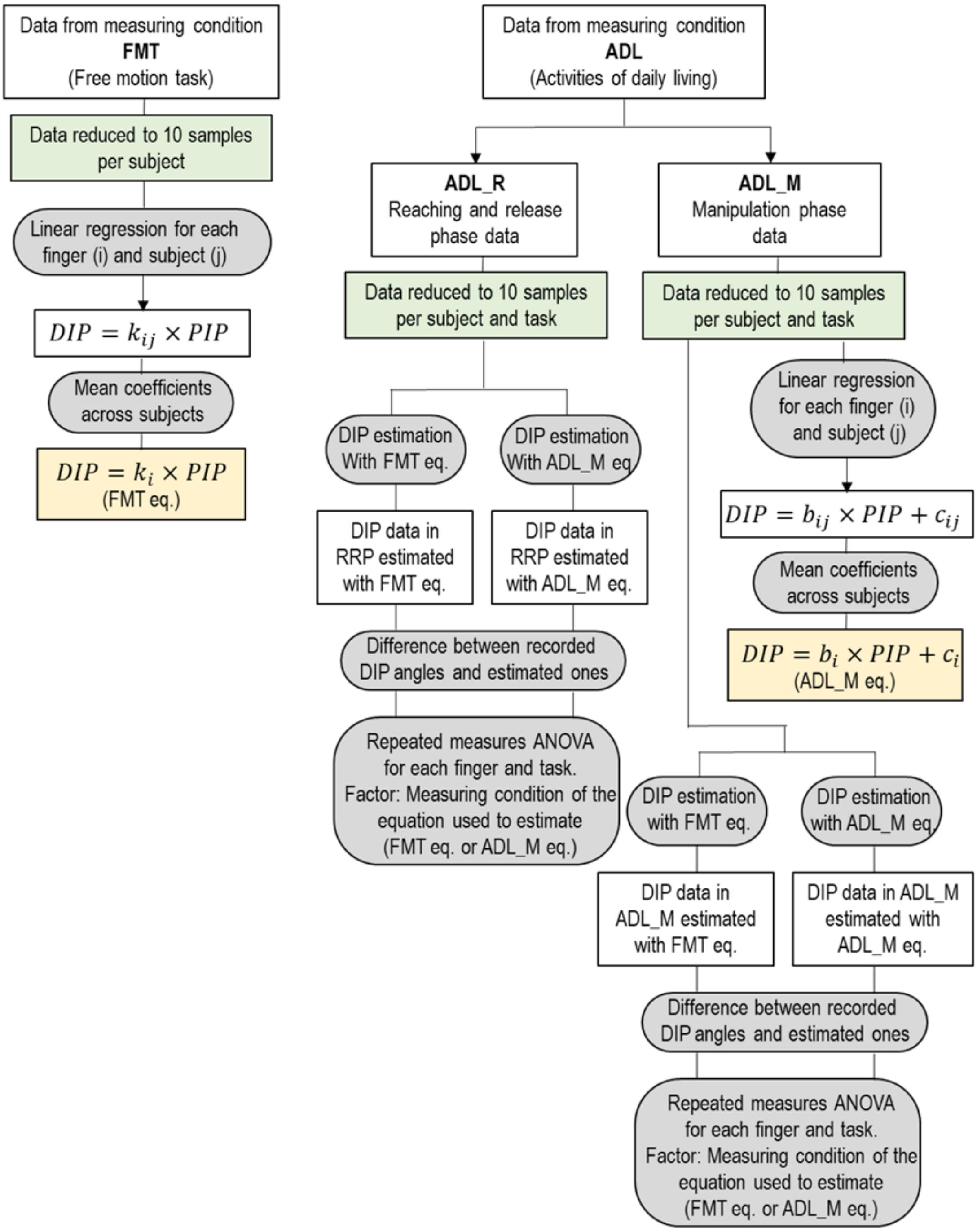


Figure 3.4.3: Flowchart of the data analysis.

3.4.3 Results

After performing both types of regressions with FMT data (assuming null and non-null constant coefficient), mean absolute errors when estimating DIP angles from PIP ones in FMT were (null vs non-null constant coefficient): 6.01° vs 6.35° for index finger, 9.38° vs 9.58° for middle finger, 6.91° vs 7.02° for ring finger and 7.48° vs 8.19° for little finger. Therefore, regression with null constant coefficient was chosen, as the error was slightly lower for all the fingers with this regression type. This is in accordance to the consideration of null or negligible constant coefficients in previous works in literature studying PIP-DIP linkage during free motion [174]–[178] Table 3.4.3 presents descriptive statistics across subjects of the regressions with null constant coefficient performed for each finger during the FMT, all with $p \leq 0.01$.

Table 3.4.3: Descriptive statistics of the slopes and R2 values in the regressions for each finger during the FMT.

FMT	SLOPE				R^2			
FINGER	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**	**Max**	**Min**
Index	0.52	0.11	0.66	0.36	0.98	0.02	0.99	0.94
Middle	0.75	0.15	0.97	0.56	0.96	0.04	0.99	0.86
Ring	0.52	0.11	0.71	0.38	0.95	0.05	0.99	0.83
Little	0.80	0.13	1.04	0.67	0.97	0.04	1	0.89

In the same way, after performing both types of regressions with ADL_M data (assuming null and non-null constant coefficient), the mean absolute errors across subjects when estimating DIP angles in ADL_M and ADL_R were computed for each finger and task (Figure AII.1 to AII.8 in Appendix II). The mean errors when estimating ADL_M data were (null vs non-null constant coefficient): 8.65º vs 8.61º for index finger, 13.09º vs 13.19º for middle finger, 10.31º vs 10.06º for ring finger and 11.57º vs 10.93º for little finger. In the same way, when estimating ADL_R data, the errors were: 4.59º vs 4.07º for index finger, 8.98º vs 9.78º for middle finger, 7.41º vs 7.69º for ring finger and 8.88º vs 8.28º for little finger.

Although the error was lower in some tasks and fingers when estimating using null constant coefficient, the overall errors were slightly lower when estimating using non-null constant coefficient in most fingers. Furthermore, almost all the constant coefficients (28 out of 36) were found to be statistically significant (Sig≤0.01), so that this regression type was chosen as the most appropriate one. Table 3.4.4 presents descriptive statistics across subjects of the non-null constant coefficient regressions performed for each finger during the ADL_M of the 26 ADLs altogether, again all with $p \leq 0.01$.

Table 3.4.4: Descriptive statistics of the slopes, constant coefficients (in degrees) and R2 values in the regressions for each finger during the ADL_M of the 26 ADLs altogether.

ADL_M	SLOPE				CONSTANT COEF.				R^2			
FINGER	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**	**Max**	**Min**
Index	0.44	0.15	0.71	0.22	-2.47	4.76	4.76	-5.66	0.48	0.19	0.81	0.13
Middle	0.81	0.19	1.22	0.59	-13.97	8.87	0.04	-28.31	0.65	0.14	0.87	0.35
Ring	0.58	0.12	0.86	0.49	-12.33	7.56	-3.71	-23.98	0.63	0.10	0.77	0.44
Little	0.87	0.20	1.21	0.65	-10.52	9.16	4.36	-21.50	0.69	0.15	0.88	0.46

Figures 3.4.4 to 3.4.11 present scatter plots for each subject of DIP vs PIP angles (showing all the data recorded) for each finger and phase (ADL_R and ADL_M). The plots represent data recorded in the 26 ADLs (a different colour per task) and the FMT regression line for each subject and finger. Analogue scatter plots but including all the data recorded in FMT are presented in Appendix II (Figures AII.9 to AII.12).

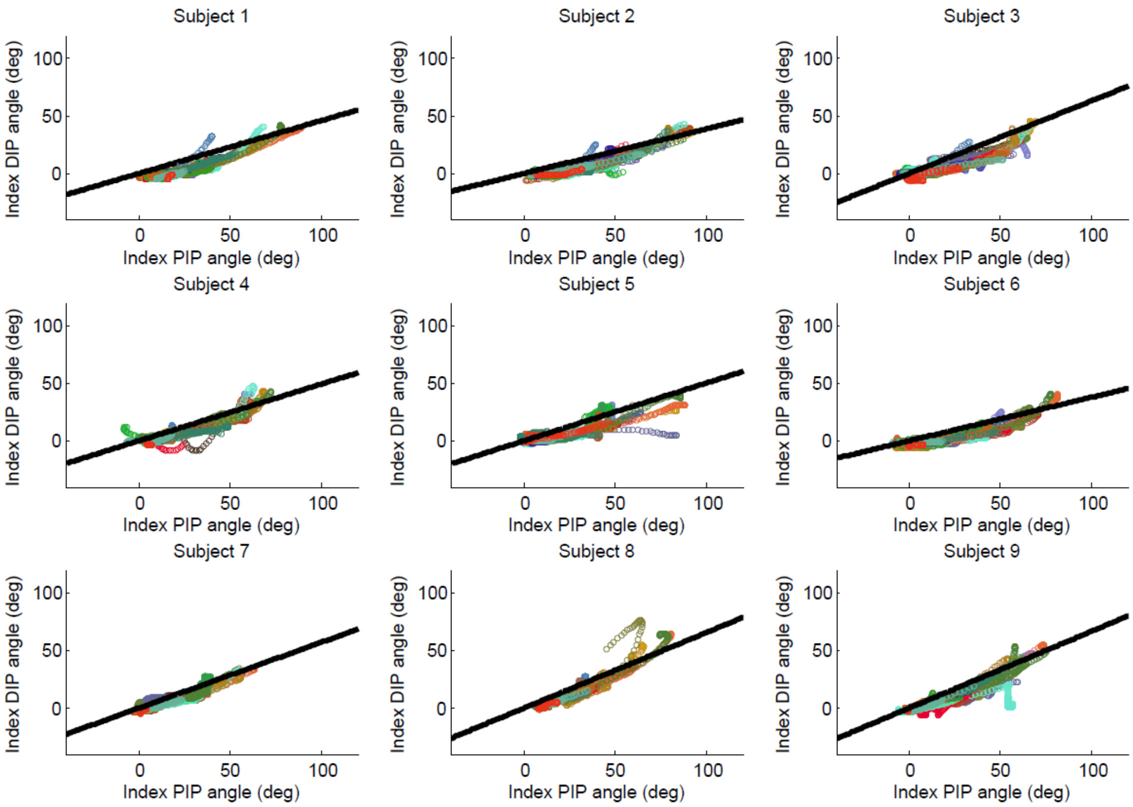


Figure 3.4.4: Scatter plots of index finger PIP and DIP angles recorded (in degrees) during ADL_R, for each subject. Each task data plotted with a different colour. Regression line of each subject's FMT data plotted in black.

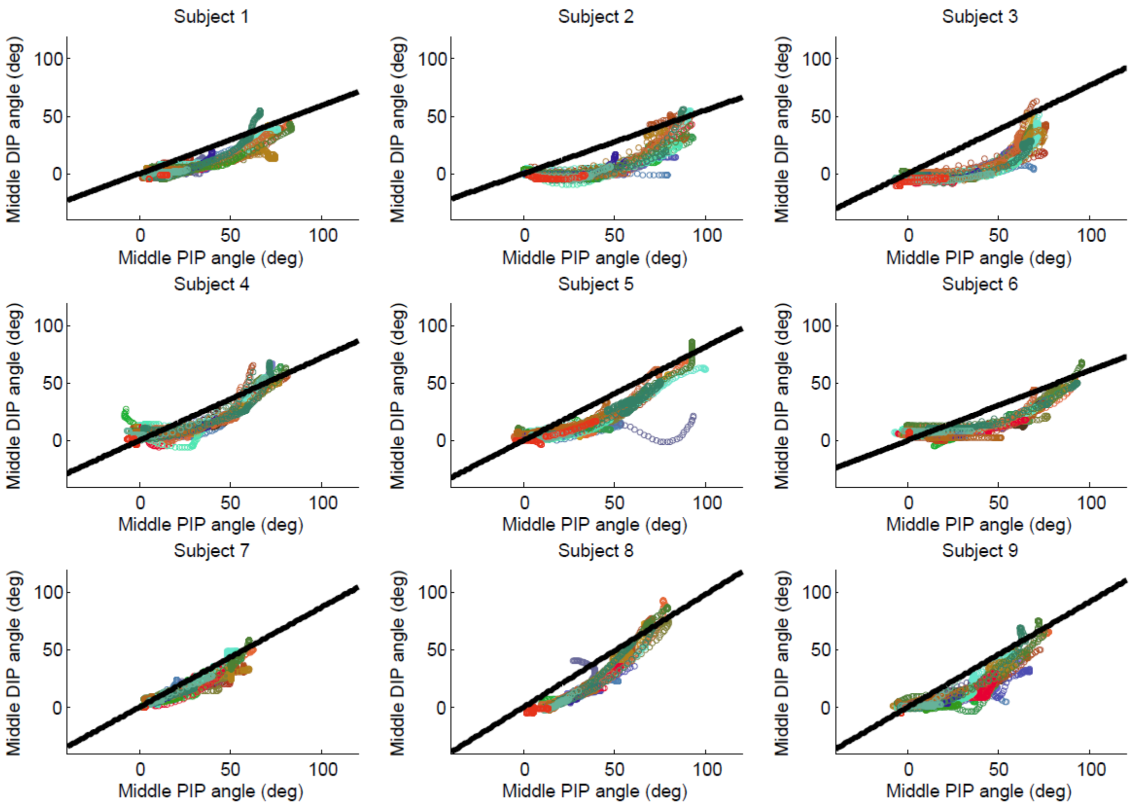


Figure 3.4.5: Scatter plots of middle finger PIP and DIP angles recorded (in degrees) during ADL_R, for each subject. Each task data plotted with a different colour. Regression line of each subject's FMT data plotted in black.

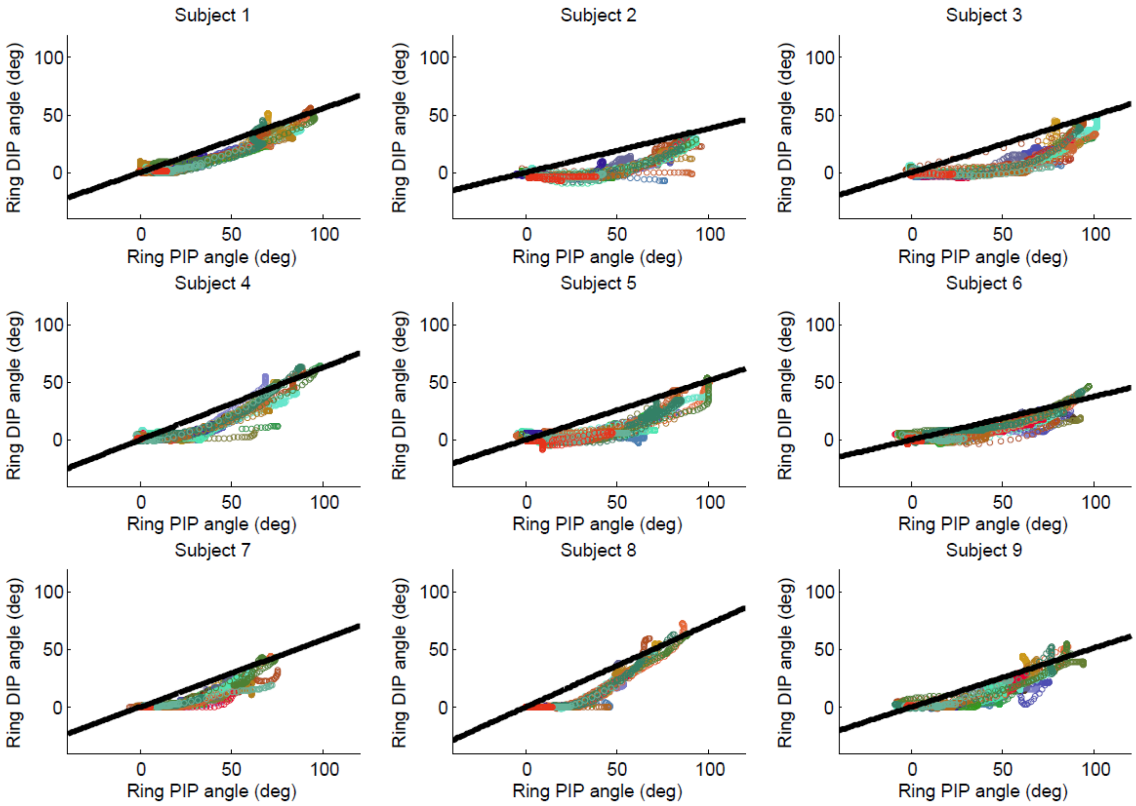


Figure 3.4.6: Scatter plots of ring finger PIP and DIP angles recorded (in degrees) during ADL_R, for each subject. Each task data plotted with a different colour. Regression line of each subject's FMT data plotted in black.

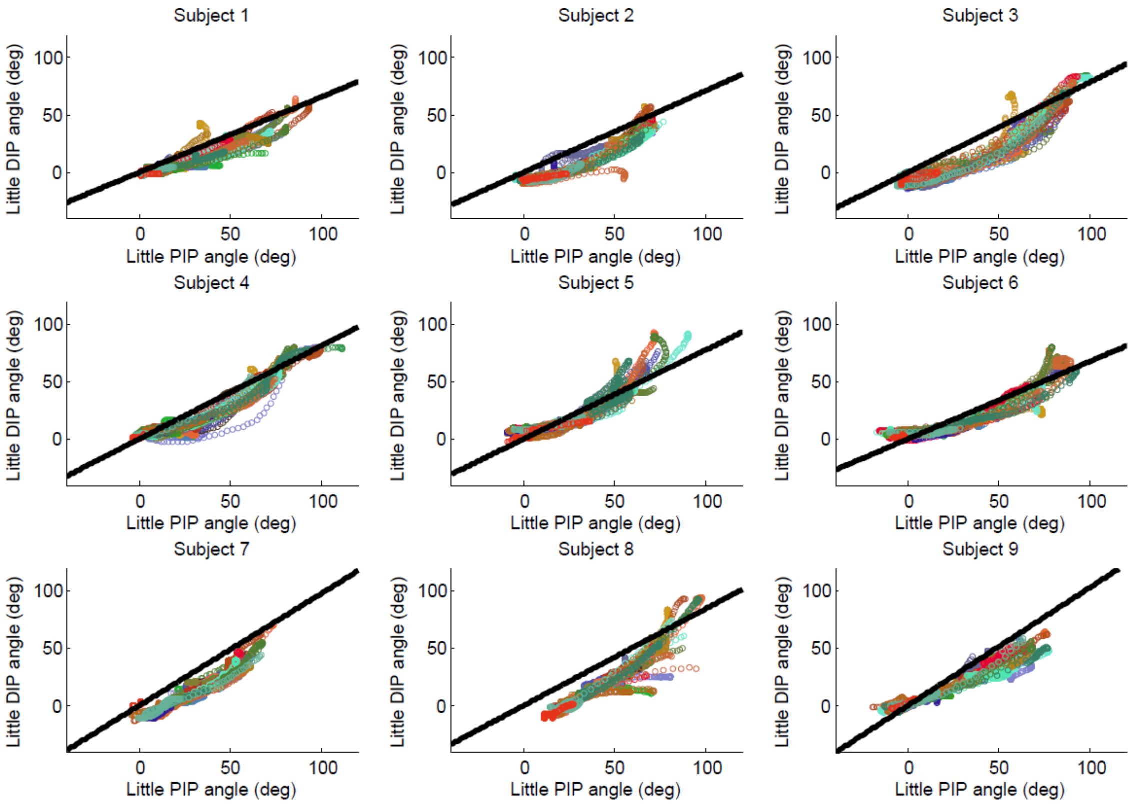


Figure 3.4.7: Scatter plots of little finger PIP and DIP angles recorded (in degrees) during ADL_R, for each subject. Each task data plotted with a different colour. Regression line of each subject's FMT data plotted in black.

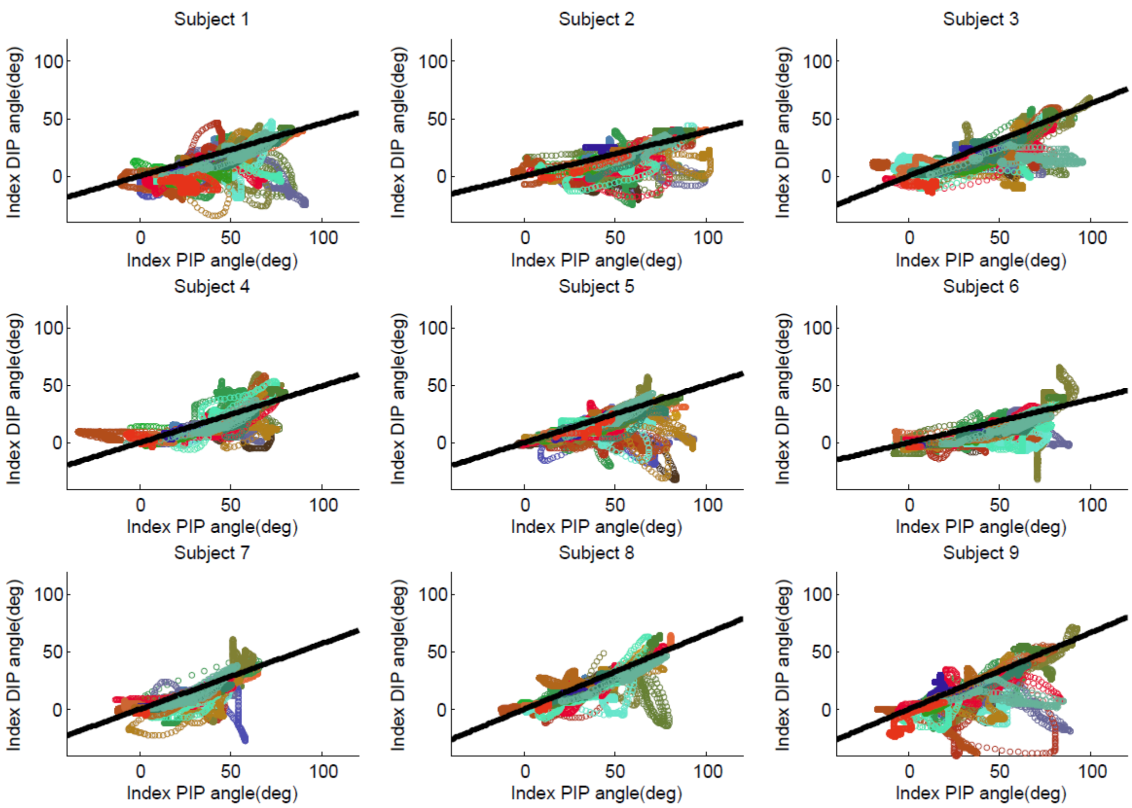


Figure 3.4.8: Scatter plots of index finger PIP and DIP angles recorded (in degrees) during ADL_M, for each subject. Each task data plotted with a different colour. Regression line of each subject's FMT data plotted in black.

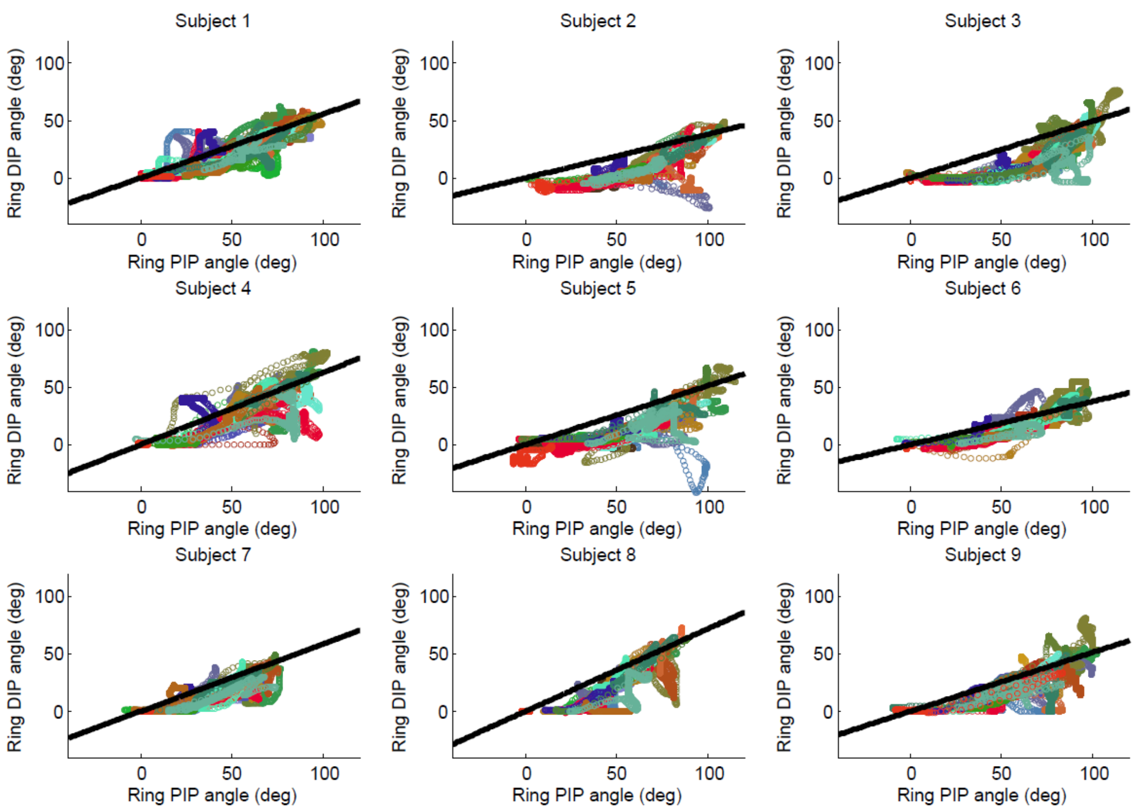


Figure 3.4.9: Scatter plots of middle finger PIP and DIP angles recorded (in degrees) during ADL_M, for each subject. Each task data plotted with a different colour. Regression line of each subject's FMT data plotted in black.

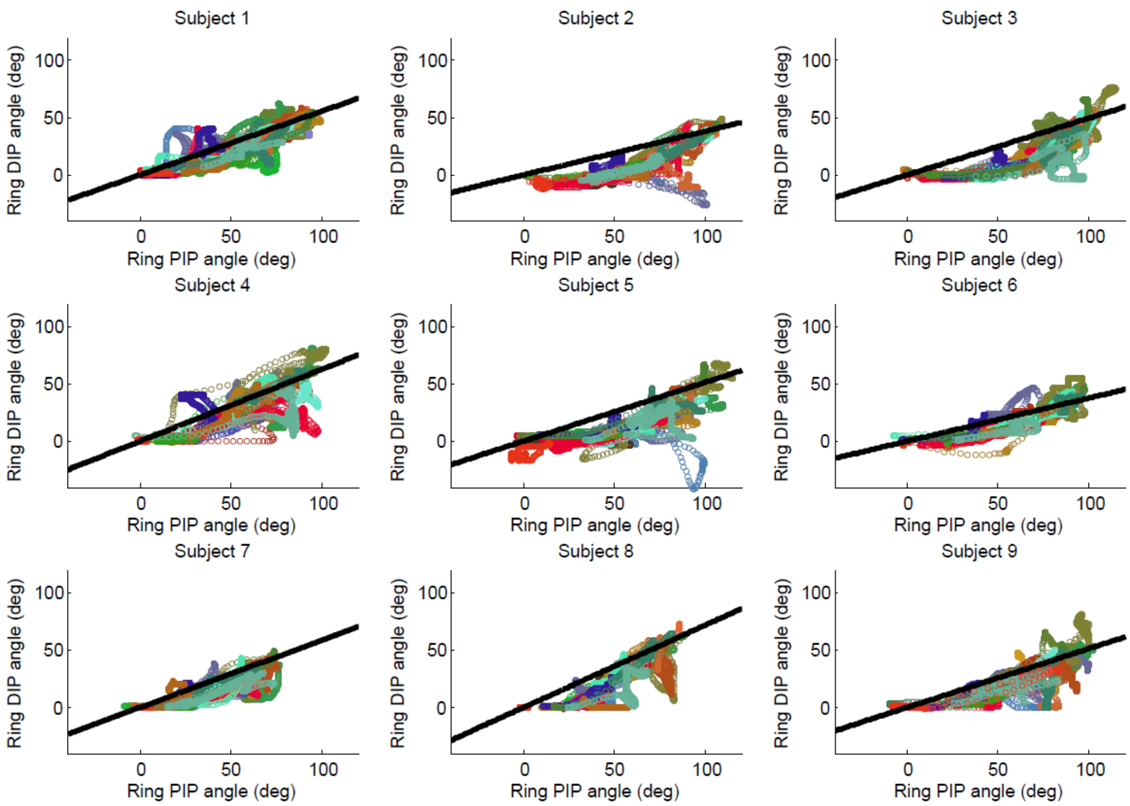


Figure 3.4.10: Scatter plots of ring finger PIP and DIP angles recorded (in degrees) during ADL_M, for each subject. Each task data plotted with a different colour. Regression line of each subject's FMT data plotted in black.

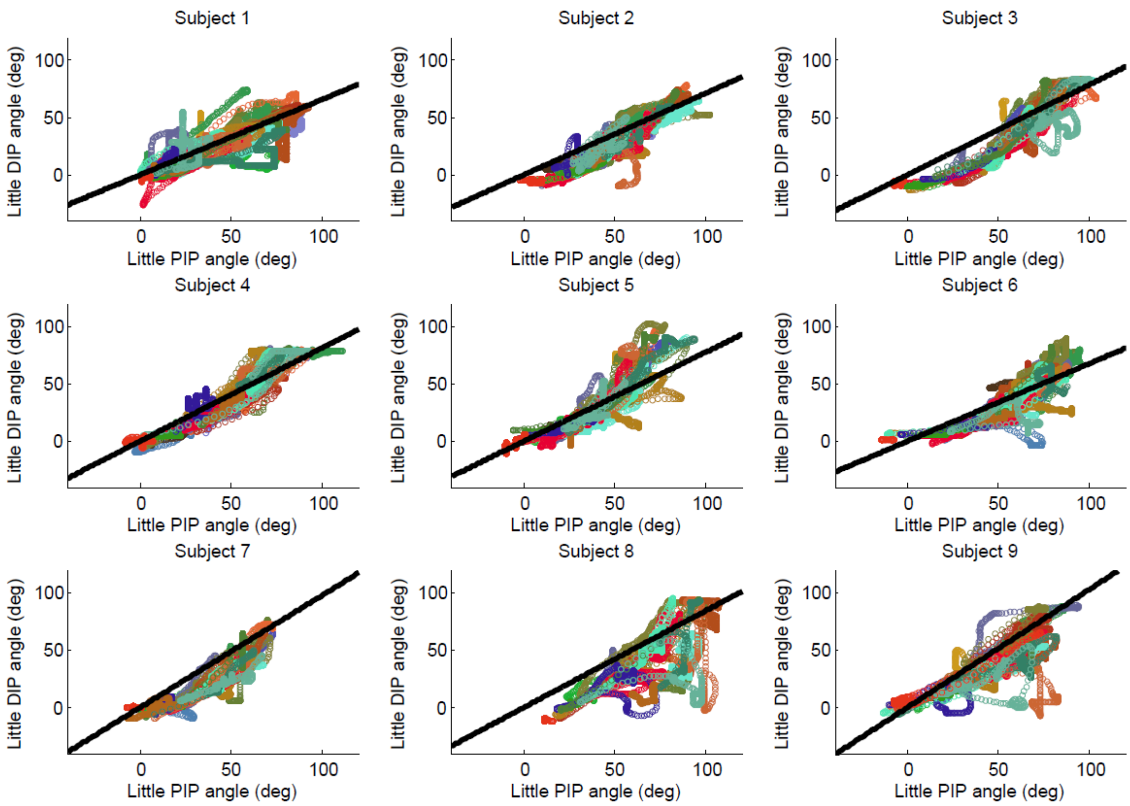


Figure 3.4.11: Scatter plots of little finger PIP and DIP angles recorded (in degrees) during ADL_M, for each subject. Each task data plotted with a different colour. Regression line of each subject's FMT data plotted in black.

Figures AII.13 to AII.16 in Appendix II present box and whiskers plots of the errors (for each finger and task) of estimating the DIP angles during ADL_M phase using both the coefficients obtained during FMT and ADL_M conditions. The tasks that presented highest absolute mean errors when estimating using FMT coefficients were writing with a pen (#16) for index finger (22.86º), unscrewing lid of jars (#11) for middle finger (23.66º), lifting wooden cubes (#4) for ring finger (19.30º) and lifting telephone receiver (#20) for little finger (20.52º). The ones that presented lowest absolute mean errors were pouring water from carton (#21) for index finger (4.79º) and cleaning the table (#26) for middle finger (7.97º), ring finger (4.12º) and little finger (7.34º). The tasks that presented highest absolute mean errors when estimating using ADL_M coefficients were writing with a pen (#16) for index finger (17.83º), pouring water from cup (#23) for middle finger (18.87º), lifting an iron (#5) for ring finger (15.04º) and lifting telephone receiver (#20) for little finger (19.19º). The ones that presented lowest absolute mean errors were picking a coin (#1) for index finger (4.31º) and little finger (4.95º), cleaning the table (#26) for middle finger (9.12º) and writing with a keyboard (#19) for ring finger (5.15º).

The repeated measures ANOVAs revealed significant differences (sig. ≤ 0.01, average observed power of 0.824) in several tasks between the estimations of the DIP angles during the ADL_M phase, using FMT or ADL_M coefficients. Table 3.4.5 lists the tasks that presented lowest error when estimating angles using the coefficients from each condition, per finger. Those that presented statistically significant differences are highlighted in grey.

Table 3.4.5: Tasks classified depending of the mean error when estimating DIP angles from PIP ones in ADL_M, classified by fingers. Tasks that presented statistically significant differences when applying the ANOVA are highlighted in grey.

	ADL_M	
	Tasks with lowest error with FMT coefficients	Tasks with lowest error with ADL_M coefficients
Index	2, 4, 5, 9, 21, 22	1, 3, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19,20, 23, 24, 25, 26
Middle	3, 5, 6,14, 20, 21, 22,26	1, 2, 4, 7, 8, 9, 10, 11, 12, 13, 15, 16, 17, 18, 19, 23, 24, 25
Ring	5, 6, 13, 21, 22, 26	1, 2, 3, 4, 7, 8,9, 10, 11, 12, 14, 15, 16, 17, 18, 19, 20, 23, 24 ,25
Little	5, 6, 9, 13, 22, 26	1, 2, 3, 4, 7, 8, 10, 11, 12, 14, 15, 16, 17, 18, 19, 20, 21, 23, 24, 25

Figures AII.17 to AII.20 in Appendix II present the box and whiskers plots of the errors (for each finger and task) of estimating the DIP angles during ADL_R using both the coefficients obtained during FMT and during ADL_M conditions. The tasks that presented highest mean absolute errors when estimating using FMT coefficients were putting tubigrip (#13) for index finger (9.00º), lifting wooden cubes (#4) for middle finger (17.87º), opening/closing a zip (#2) for ring finger (15.75º) and little finger (15.84º). The ones that presented lowest absolute mean errors were pouring water from carton (#21) for index finger (4.47º) and cleaning the table (#26) for middle finger (6.49º), ring finger (4.02º) and also little finger (error of 6.70º). The tasks that presented highest mean absolute errors when estimating using ADL_M coefficients were opening/closing a zip (#2) for index finger (5.87º), pouring water from jug (#22) for middle finger (13.67º), putting tubigrip (#16) for ring finger (11.08º) and lifting an iron (#5) for little finger (10.89º). The ones that presented lowest absolute mean errors were pouring water from carton (#21) for index finger (2.38º), doing up buttons (#12) for middle finger (7.03º), unscrewing lid of jars (#11) for ring finger (4.98º) and putting key into lock and turning it (#8) for little finger (6.00º).

The repeated measures ANOVAs revealed significant differences (sig. ≤ 0.01, average observed power of 0.745) in several tasks between the estimations of the DIP angles during the ADL_R phase, using FMT or ADL_M coefficients. Table 3.4.6 lists the tasks that presented lowest error when estimating angles using the coefficients from each condition, per finger. Those that presented statistically significant differences are highlighted in grey.

Table 3.4.6: Tasks classified depending of the mean error when estimating DIP angles from PIP ones in ADL_R, classified by fingers. Tasks that presented statistically significant differences when applying the ANOVA are highlighted in grey.

	ADL_R	
	Tasks with lowest error with FMT coefficients	Tasks with lowest error with ADL_M coefficients
Index		1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26
Middle	15, 16, 17,21,22, 23, 25, 26	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19, 20, 24
Ring	14, 16, 17, 18, 21, 22, 23,25, 26	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 19, 20, 24
Little	26	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25

3.4.4 Discussion

The slopes obtained in the FMT are within the range of values reported in literature (Table 3.4.1). However, they are larger for middle and little fingers (0.75 and 0.80, respectively) than for index and ring fingers (0.52), and this distribution of slopes among fingers does not match the ones reported in literature, which are neither consistent. These differences may be attributable to the way of performing the free movement in the experiments. While other works considered a movement of closing the fist, here MCP joints were asked to be kept in neutral position while PIP and DIP joints were flexed, so as to separate the PIP-DIP flexion relationship from the MCP flexion. Moreover, the movement of closing the fist, used in reported works, could have limited DIP flexion in some occasions because of the contact of the fingertips with the palm (Figure 3.4.11), not being exactly representative of pure free motion.

Figure 3.4.11: DIP flexion limited by the contact of fingers with palm.

The slopes obtained herein could have been affected to a lesser extent by the stiffness of the instrumented glove. Nevertheless, this stiffness is expected to affect both PIP and DIP flexion to a similar extent, not affecting significantly to the flexion ratio.

Mean slopes across subjects obtained for middle, ring and little fingers are higher in ADL_M than in FMT (0.81 vs 0.75 in middle finger, 0.58 vs 0.52 in ring finger and 0.87 vs 0.80 in little finger). Nevertheless, they are compensated in ADL_M by significant offsets of -13.97º (middle finger), -12.33º (ring finger) and -10.52º (little finger). Index finger is the only one that presents lower slope in ADL_M than in FMT (0.44 vs 0.52). Furthermore, it presents the lowest R squared value (0.48) among all the fingers and phases when performing the regression with ADL_M data. This lower slope and bad fitting may be attributable to simultaneous active PIP flexion and passive DIP extension occurring during certain grasp types, especially pinch grasps (see Figure 3.4.12), therefore becoming into negative slope values. This can be clearly observed in the scatter plots of PIP vs DIP of index finger during ADL_M (Figure 3.4.8). This passive DIP extension during PIP flexion, apart from reducing mean slope values for this finger, also becomes into a worst data fitting.

Figure 3.4.12: Grasp with active flexion of index PIP joint and passive extension of index DIP joint.

The scatter plots of DIP vs PIP angles during ADL_R (Figures 3.4.4 to 3.4.7) demonstrate that the PIP-DIP linkage in the free motion during ADLs (i.e. ADL_R) is quite similar to the FMT one (except in some tasks). Despite the fact that in general terms the data fit quite well to the linear regression obtained during the FMT, the range of motion is lower in ADL_R and in some specific tasks PIP joint flexes while DIP joint is kept almost in neutral position. This happens only in some subjects, probably owing to their specific ligamentous system: when approaching to an object to perform certain grasps (e.g. a 2 or 3 finger pinch), the fingers that do not participate in the grasp are folded apart by flexing PIP joints while DIP joints remain in neutral position (Figure 3.4.13, left). DIP joints can be passively extended in other cases when fingertips contact the palm (Figure 3.4.13, right).

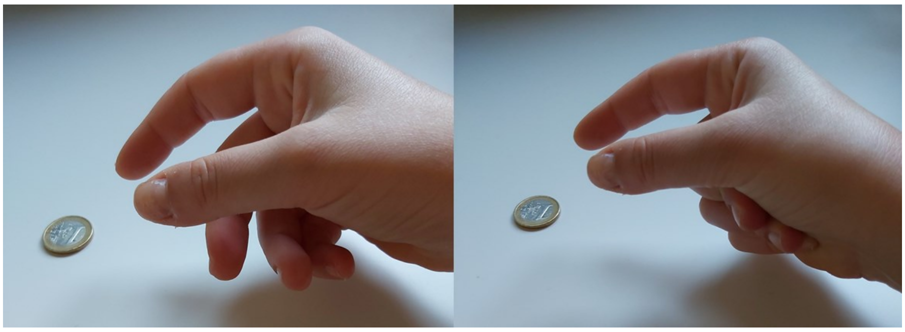


Figure 3.4.13: LEFT: Middle to little fingers (which do not participate in the grasp) folded apart during reaching. RIGHT: Middle to little fingers (which do not participate in the grasp) with passive DIP extension during manipulation.

Both ADL_R and FMT scatter plots (Figure 3.4.4 and Figure AI.1, respectively show a linear relationship for the index finger. Nevertheless, data from middle, ring and little fingers of certain subjects seem to fit better to a parabolic function (Figure 3.4.5 to Figure 3.4.7 and Figure AI.10 to Figure AI.12, as DIP joints do not experience any flexion for low PIP flexion.

Contrarily, scatter plots of DIP vs PIP angles during ADL_M show poor linearity (Figure 3.4.8 to Figure 3.4.11), and only in few fingers and subjects the data fit approximately to the corresponding FMT regression line. The index finger is the one with more extreme data points (i.e., farthest from the regression line), as it is generally more involved in grasping than the other fingers. These extreme data points are usually under the FMT regression line, but rarely above it. Again, this is due to the passive DIP extension or to maintaining neutral posture during PIP flexion. This configuration is largely more common during manipulation than flexing DIP joint while PIP is kept neutral (which would generate points above the FMT regression line); this is unnatural even during manipulation (note the reference to PIP neutral position, rather than extension, as this joint has almost no extension range of motion).

Box and whiskers plots of the errors arisen when estimating data present higher dispersion in ADL_M phase (Figures AI.13 to AI.16) than in ADL_R phase (Figures AI.17 to AI.20), but all of them present similar bias. It is remarkable that for all the phases, fingers and tasks, differences between measured and estimated DIP joint angles are larger when estimated using FMT coefficients than when using the ADL_M ones. Therefore, FMT coefficients tend to overestimate the DIP flexion angles: even though ADL_M slopes are higher than FMT ones (except for index finger), the negative constant coefficients in ADL_M regressions significantly reduce the estimated flexion values.

Regarding the error arisen when estimating DIP angle from PIP angle in ADL_M using ADL_M and FMT coefficients, Table 3.4.5 shows that those tasks that present lowest errors when estimated using FMT coefficients are those that require a cylindrical grasp for their performance, and the diameter of the object to grasp is small. Among these tasks, those that present statistically significant lowest error in more than one finger are lifting an iron (#5), pouring water from jug (#22) and cleaning the table (#26).

Contrarily, those that present lowest errors when estimated using ADL_M coefficients are those that require a grasp where passive extension of DIP joint can appear while flexing PIP joint (as pinch or non-prehensile grasps) as consequence of the pressure applied during the grasp, as well as because of the shape of the manipulated object. Furthermore, as mentioned previously, when performing certain grasps (e.g. a 2 or 3 finger pinch), some subjects tend to fold apart the fingers that do not participate in the grasp by flexing PIP joints while keeping DIP joints in neutral position. These tasks that presented statistically significant lowest error in more than one finger are putting a coin into a purse (#1), zipping/unzipping a purse (#2), picking up a coin from a purse (#3), lifting wooden cubes (#4), putting nuts on bolts (#7), putting key into lock (#8), tying a shoe (#10), unscrewing lid of jars (#11), doing up buttons (#12), eating with a spoon (#15), writing with a pen (#16), folding a paper and putting into envelope (#17), putting a paper-clip on envelope (#18), writing with a keyboard (#19), pouring water from cup (#23), putting toothpaste in toothbrush (#24) and spraying the table (#25).

As to the error arisen when estimating DIP angle in ADL_R using ADL_M and FMT coefficients, Table 3.4.6 clearly shows that only the task cleaning the table with a tea towel (#26) presents statistically significant lowest errors in more than one finger when performing the estimation using FMT coefficients. On the other hand, many tasks present statistically significant lowest error in more than one finger when estimated using ADL_M coefficients: putting a coin into a purse (#1), zipping/unzipping a purse (#2), picking up a coin from a purse (#3), lifting wooden cubes (#4), lifting an iron (#5), using a screwdriver (#6), putting nuts on bolts (#7), putting key into lock (#8), turning a door-handle (#9), tying a shoe (#10), unscrewing lid of jars (#11), doing up buttons (#12) and putting a tubigrip (#13). This is attributable to the fact that PIP and DIP joints do not achieve the same degree of flexion in ADL_R as in FMT (see scatter plots for ADL_R and FMT). As mentioned previously, data in ADL_R presents a parabolic fitting shape, as DIP does not start to flex until certain degree of PIP flexion. Therefore, regression line of ADL_R data would be more similar to the ADL_M one (lower slopes) than to the FMT one.

3.4.5 Conclusions

The main outcome of this work has been the assessment of the error arisen when estimating DIP joint angles assuming experimental linear relationship with PIP joint angles, depending on the task performed (and consequently, on the grasp type used). The estimation of DIP joint angles using the slopes obtained from FMT implies low absolute errors in grasps or tasks where both PIP and DIP are highly flexed. Even though the estimation using ADL_M coefficients implied lower mean absolute error per task (<5.87º for index finger, <13.67º for middle, <11.08º for ring and <10.89º for little) than using FMT ones (<9º for index finger, <17.87º for middle, <15.75º for ring and <15.84º for little), it fails to provide accurate estimations in many cases: passive extension of DIP joints may occur while PIP is flexed, and postures are quite dependent on objects' shape and pressure applied during grasping. Therefore, attending to results from this study, estimating DIP joint angles from PIP ones is only recommended in case of studying free motion or grasps where both joints are highly flexed and using FMT coefficients (the mean error under these conditions was, in this case, taking for each finger the tasks that presented statistically significant lower errors, 5.92º for index finger, 12.21º for middle, 8.61º for ring and 11.12º for little), but not in other conditions.

3.5 Evaluation of an instrumented glove with pressure sensors

An abstract of the work presented in this section was presented in the 8th World Congress of Biomechanics (2018) under the title "Evaluation of an instrumented glove for its use in the kinematics characterisation during product manipulation".

3.5.1 Introduction

The CyberGlove (CyberGlove Systems, San Jose, CA, USA) (Figure 3.5.1) is the most used instrumented glove in biomechanics in order to record hand kinematics. Its main body, as mentioned previously, is made of elastic fabric, thicker in the reverse of the hand and thinner in the palm, what contributes to its fitting. All the wiring and strain gauges are located on the reverse of the hand in order not to hinder manipulation, and each gauge position is fixed by means of seams. This glove has a thin and well distributed wiring, owing to the thinness of strain gauge sensors.

Figure 3.5.1: CyberGlove II instrumented glove.

The Cyberglove, however, needs to use visual analysis to distinguish between reaching, manipulation and release during product manipulation in activities of daily living, which might be interesting in many cases. This visual distinction consists in recording the time stamp of certain events using the data acquisition software. These time stamps allow splitting recordings in several parts at convenience (e.g. in reach, grasp and release phases) or identifying certain events (e.g. the performance of a specific grasp). Nevertheless, acquiring time stamps though visual analysis requires a person observing all the tasks performed, and also implies an error associated to its time of response. An alternative to this visual analysis could be automating the procedure by using a glove including pressure sensors.

There are some commercial gloves developed for virtual reality applications, as the Virtual Motion Glove 30 (VMG30) (Figure 3.5.2), that are also equipped with pressure sensors to detect contact with objects. The VMG30, apart from being equipped with strain gauges allowing the measurement of the same 18 DoF as the CyberGlove 18-DoF, also has 5 pressure sensors at the fingertips. The B&E research group has a VMG30 glove with 5 additional pressure sensors installed on the palm and on the proximal phalanx of the middle finger (Figure 3.5.3 shows the location of all the sensors). The main body of the glove is made of elastic fabric, but the fitting is not as good as in the CyberGlove (Figure 3.5.4) because the bulky wiring embedded, and also because of the tailoring of the glove. The glove is also fixed to the wrist with a Velcro strap, and the fingertips are covered. In this glove the wiring of the gauges is located in the reverse of the hand as well, and the pressure sensors and its wiring (not very optimized and bulky) in the palm and fingers.

Figure 3.5.2: Virtual Motion Glove 30.

Figure 3.5.3: Pressure sensors location: s1 to s5 on the fingertips; s6, s7, s9 ands10 on the palm; s8 on the middle proximal phalanx.

Figure 3.5.4. Same subject wearing a CyberGlove (left hand) and a VMG30 (right hand).

The aim of this work is to evaluate the feasibility of using the VMG30 for characterising the hand kinematics during product manipulation, regarding its accuracy for motion recording when compared with CyberGlove, along with its ability to distinguish manipulation through its pressure sensors when compared with visual analysis.

3.5.2 Methods

Some pilot experiments were performed on a limited number of subjects in two different phases, which consisted of testing the kinematic accuracy of VMG30 recordings (Phase I) and studying VMG30 detection sensitivity when contacting objects (Phase II) while performing a set of tasks. VMG30 and CyberGlove II (both right gloves of 18 DoF) were used to acquire data during the experiment.

All the experiments were approved by the University ethics committee. All the subjects were previously informed about the characteristics of the experiment and gave their written consent to participate.

Phase I

Three subjects with different hand sizes and ages (Subject 1: 174mm, 49 years; Subject 2: 196mm, 48 years; Subject 3: 176mm, 44 years) volunteered to participate in Phase I. In this phase, in order to assess the kinematic accuracy of VMG30, the active ranges of motion (AROMs) of 16 hand joints angles (Figure 3.5.5 and Table 3.5.1) were recorded with both gloves. After recording, joint angles were computed using the calibration coefficients obtained for each glove, according to [23]. Then, joint angles obtained from both gloves were filtered with a 2nd order two-way low pass Butterworth filter with a cut-off frequency of 5Hz. The AROM for each subject and joint was computed from these filtered angles, and the mean values across subjects were computed. Mean AROMs obtained for each joint when using VMG30 and CyberGlove were compared with a repeated measures ANOVA.

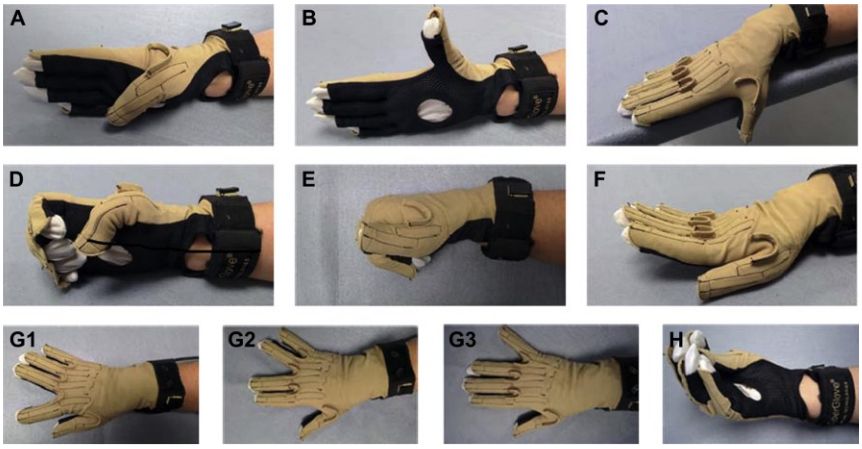


Figure 3.5.5: Postures recorded to assess the active range of motion of the different hand joints (See Table 3.5.1)

Table 3.5.1: Active range of motion assessed in each recording presented in Figure 3.5.5.

Posture	Active range of motion assessed
A	Max. thumb CMC flexion (CMC1_F)
B	Max. thumb CMC extension (CMC1_E)
C	Max. thumb CMC abduction (CMC1_A)
D	Max. thumb interphalangeal joint (IP1_F) and metacarpophalangeal joint flexion (MCP1_F)
D	Max. proximal interphalangeal joint flexion of index to little fingers (PIP2_F-PIP5_F)
E	Max. metacarpophalangeal joint flexion of index to little fingers(MCP2_F-MCP5_F)
F	Max. metacarpophalangeal joint and proximal interphalangeal joint extension of index to little fingers (PIP2_E-PIP5_E) (MCP2_E-MCP5_E)
G1	Max. abduction between index and middle fingers (MCP2_A)
G2	Max. abduction between middle and ring fingers (MCP4_A)
G3	Max. abduction between ring and little fingers (MCP5_A)
H	Max. flexion of carpometacarpal joint (CMC5)

Phase II

Subjects 1 and 2 from Phase I volunteered to participate in Phase II. In this phase, in order to assess the manipulation detection capabilities, 6 activities (A1 to A6, Figure 3.5.6) representative of several grasp types and involving different objects were performed by two subjects while wearing the VMG30. The material used to perform the tasks A1, A2, A5 and A6 belonged to the Sollerman Hand Function Test [82].

Figure 3.5.6: Activities performed in the manipulation detection experiment.

The person in charge of the experiments recorded the time stamp of the instants where grasp and release of the objects occurred in each activity (using the data acquisition software), as part of the visual analysis. After this, time stamps collected in visual analysis were compared with those from the activation of any of the pressure sensors with a paired t-test.

3.5.3 Results

Results from Phase I showed no significant differences (Sig.>0.05) in the flexion-extension and abduction AROMs (Figure 3.5.7) obtained with both gloves, although some extremely high flexion values appeared at the metacarpophalangeal joints. These extreme values are attributable to the coefficients obtained from the calibration process in these joints, which may not be appropriate. Researchers experienced several problems when placing the initial calibration accessories on the hand dorsum because of the wiring of the glove, which is bulky and not uniformly distributed, which might have affected the performance of the entire calibration.

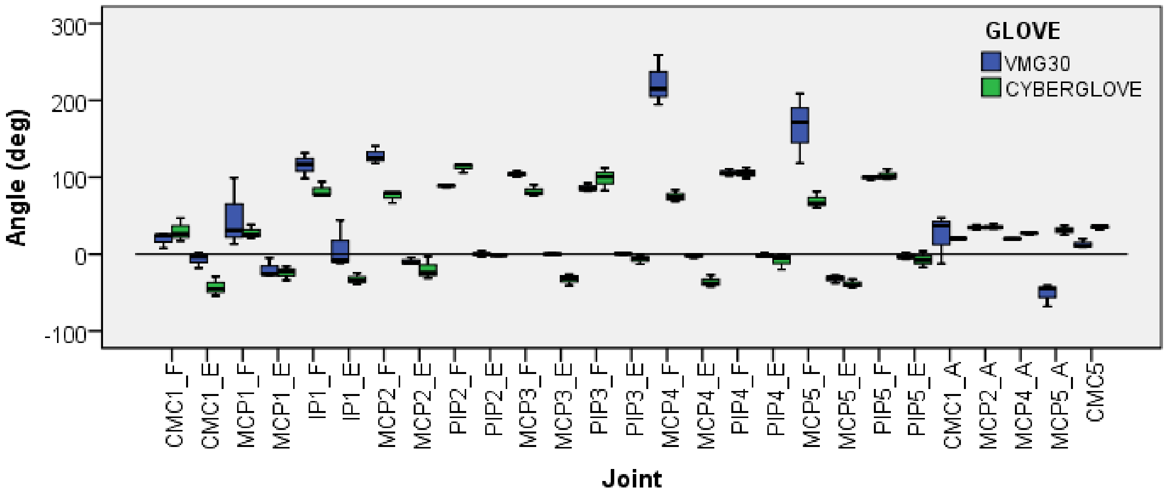


Figure 3.5.7: Box and whiskers plot of AROMs (deg) recorded for each subject with both gloves. Joint movements labelled as described in Table 2.5.1.

In the contact detection study (Phase II) pressure sensors detection clearly failed (differences with visual analysis higher > 1s) in two occasions: when releasing a knife and grasping a pen, because of lack of sensitivity. Furthermore, some sensors were frequently activated (s1, s2, s3), while others were rarely or not activated at all (s4, s10) (Table 3.5.2 and Figure 3.5.7). These differences can be produced by different factors as sensitivity or bad fit of glove in small hands and the selected activities/products. In fact, subjects reported some difficulties with the completion of some activities due the thickness and stiffness of the VMG30. No significant differences (0.03s ± 0.50s) were found between visual analysis and pressure sensors detection (smallest differences marked in blue in Table 3.5.2). Moreover, no bias was observed in pressure sensors activation, they were activated after or before visual analysis time stamp, indistinctly.

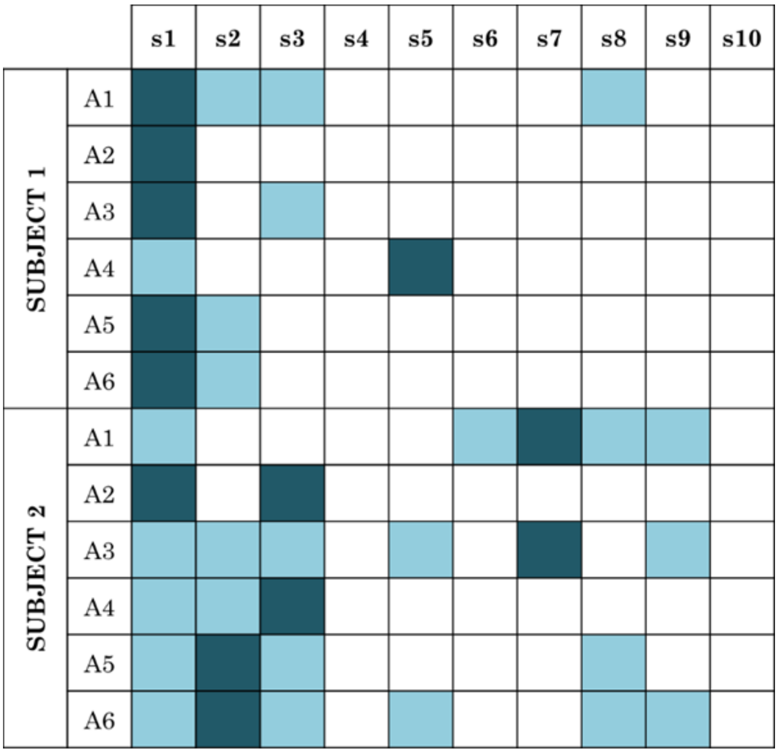


Table 3.5.2: Sensors (s1 to s10) activated in each activity (A1 to A6) for each subject. Smallest differences (<1s) marked in dark blue.

3.5.4 Conclusion

Owing to the results obtained in this experiment, VMG30 would require a re-design in order to be used in the kinematics characterisation during product manipulation. Pressure sensors should have higher sensitivity to allow automatic detection of manipulation and also higher flexibility to reduce the overall glove stiffness. Otherwise, the sensors would not offer any advantage or additional precision regarding the visual analysis technique (which also implies human errors), as obtained from the paired t-test. Furthermore, another important weakness of the glove is the wiring on the dorsum of the hand, which should be modified in order to reduce glove stiffness and to favour the placement of accessories during the initial calibration procedure. This may contribute to increase the accuracy of kinematic data recordings of the VMG30, which has been observed to be worse than that of the CyberGlove. Moreover, reducing its stiffness would also have an effect on manipulation dexterity, as observed in section 3.2. With the current characteristics of each glove and taking all the outcomes into account, the CyberGlove is still being the best choice for the experiments intended to perform.

3.6 Conclusions

As explained when introducing this chapter, instrumented gloves were initially chosen as the most appropriate motion capture system for the experiments required in this thesis, owing to the type of data required and the characteristics of the experiments to be performed. Nevertheless, B&E researchers were already aware of some problems when using instrumented gloves. Reduction of manipulation skills or poor gauge fitting (among others) were some of the main concerns of the researchers. Therefore, a set of experiments were conducted focused on studying and quantifying these problems, in order to consider all this information for planning the experiments and subsequent data analysis.

In section 3.2, wearing instrumented gloves was shown to reduce manipulation skills, especially when performing tasks requiring fine motor skills. This reduction of skills results in larger time of task performance, which may affect some kinematic parameters such as velocities. These outcomes were obtained when performing the experiments with the 18DoF CyberGlove. This model is tailored with uncovered fingertips. Contrarily, the 22DoF CyberGlove has covered fingertips, which reduces touch sensitivity, as reported by subjects after the experiment presented in section 3.3. This suggests that the reduction of manipulation skills when wearing the 22DoF CyberGlove might be even higher than that observed when wearing the 18DoF one. Furthermore, the 22DoF CyberGlove is slightly larger in order to locate the extra gauges to record the DIP joints. For this reason, it does not fit properly to small and mid-sized hands, hindering manipulation and not recording correctly both PIP and DIP joint angles. Therefore, 18DoF CyberGlove would be better choice than 22DoF CyberGlove regarding manipulability.

Another issue that was considered before running the experiments of the thesis was the possibility of using a glove with pressure sensors (VMG30), available at the Biomechanics & Ergonomics Lab, to automatically label the recordings in order to distinguish between free motion and manipulation during the tasks to be recorded. The CyberGlove does not have pressure sensors, and therefore, the distinction has to be performed by visual analysis, which is time consuming. No significant differences have been found in accuracy when labelling by visual analysis vs automatically. But the VMG 30 has been found to be less accurate than CyberGlove when recording kinematic data, and wiring design to allocate the pressure sensors is bulky, hindering the performance of tasks in a realistic way. Furthermore, the VMG30 glove has covered fingertips, with problems of fitting and touch sensitivity. For all these reasons, VMG30 was discarded for the experiments.

The 18DoF CyberGlove was therefore chosen as the most appropriate equipment (available at the B&E Lab) for conducting the experiments of the thesis. However, this glove does not allow DIP joints recording. As a mechanical linkage between DIP and PIP joint angles has been described in previous literature studies, the possibility of estimating DIP angles using PIP - DIP correlations was explored. Unfortunately, the errors when estimating DIP from PIP angles were found to be highly dependent on the task and grasp type performed, owing to forced postures because of contact forces and to adaptation to object shape that appear during object grasping and manipulation. Therefore, providing DIP angles as estimations from the PIP ones during product manipulation was discarded. Nevertheless, future works may address the estimation of DIP angles by considering the kinematic synergies observed during ADLs.

All the outcomes from this chapter, apart from helping to plan the experiments of this thesis, may be useful for the research group and to other researchers studying hand kinematics.

Chapter 4

Hand kinematics in feeding and cooking tasks

4.1 A new hand kinematics dataset for feeding and cooking tasks

The work presented in this section was published in Scientific Data (2019) 6(1):167 as a Data Descriptor under the title "Human hand kinematic data during feeding and cooking tasks".

4.1.1 Introduction

The hand is a complex system, with many degrees of freedom (DoF), that enables humans to perform a large variety of grasping and manipulation actions required in activities of daily living (ADLs), using a wide range of objects. Hand kinematics is being studied for purposes such as characterizing healthy hand movement patterns [106], assessing patients' abilities [213] or the effect of object design on grasping [147]. Furthermore, with the rise in robotics and prosthetics, it has become crucial for the development of anthropomorphic systems [214]. For these purposes, and because of the versatility of the hand, a large amount of kinematic data (for all hand DoF) is needed to cover the interaction with the different objects used in different environments. Continuous recording of kinematics is essential to characterise the range of motion and velocities required for the different phases of reaching, grasping, manipulating and releasing. Moreover, data presented as anatomical angles are more meaningful and facilitate the comparison of data from different experiments independently of the motion capture system used. In this sense, several researchers [215] have pointed out the importance of high-quality open-access datasets of grasping data, while also highlighting the need to compile, classify and standardize these data.

The *Hand Corpus* open repository (http://www.handcorpus.org) was created to undertake these goals, as it allows scientists to share grasping and manipulating data collected using different motion capture technologies. Nevertheless, the datasets in this repository, as well as the other datasets in the literature, present some weaknesses regarding their usability in machine learning, hand kinematics characterization or clinical evaluation. Some datasets offer limitations regarding the amount of data presented, are limited to grasp type classification [131], [216] or consider hand kinematics from just three markers on the hand [217]. Furthermore, datasets with several DoF present other limitations:

- **Tasks:** Only reaching and grasping movements [103], [108], [112], [116], [123], [124], static grasp postures [103], [104], [107], [108], [110], [116], [124] or exploratory/haptic tasks[117] were recorded during product manipulation. These tasks lack representativeness of ADLs because of the limited range of activities considered but also because subjects performed the tasks following precise instructions.
- **Objects used:** Some of the datasets recorded tasks simulating the use of objects, but not using any object [104], [107], [110], [112]–[114].
- **Type of data presented:** Some datasets only provide raw data from the motion capture system (cameras or gloves) [113], [114], [116] instead of offering anatomical angles.
- **Number of subjects:** Some of those datasets provide data from only one subject [103], [104], [107], [110], [112]–[114].
- **Number of hands studied:** All the datasets cited only studied subjects' dominant hand.

Table 4.1.1 shows an overview of different datasets focused on hand kinematics and their characteristics.

Table 4.1.1: Main characteristics of datasets focused on hand kinematics.

Dataset	Objects	Subjects	Tasks	Motion capture system	Type of data
NTUA[103]	4	1	Static grasps, reach and grasp	CyberGlove	Joint angles (20 DoF)
UNIPI [104], [105]	Imagined	1	Static grasps	Phase Space	Joint angles (15 DoF)
UNIPI-ASU [106], [107]	Imagined	1	Static grasps	CyberGlove	Joint angles (15 DoF)
DLR [106], [108]	23	7	Static grasps, reach and grasp	Vicon	Joint angles (20 DoF)
DLR [109], [110]	None	1	Static postures	MRI	Hand model (24 DoF)
UNIPI [111], [112]	Imagined	1	Reach and grasp	Phase Space	Joint angles (24 DoF)
UNIPI [111], [113]	None	1	Free space	Phase Space	Raw data (24 DoF)
UNIPI [111], [114]	None	1	Free space	Phase Space	Raw data (26 DoF)
TU Berlin 1 – IJRR [115], [116]	14	5	Static grasps, reach and grasp	CyberGlove	Raw data (23 DoF)
UNIPI [111], [117]	2	1	Haptic exploration	Phase Space	Joint angles (26 DoF)
HUST [118], [119]	14	30	Reach and grasp	CyberGlove	Joint angles (16 DoF)
TUB [120], [121]	25	17	Reach and grasp	CyberGlove	Raw data (21 DoF)
UNIPI [122], [123]	21	6	Reach and grasp	Phase Space	Joint angles (20 DoF)
NINAPRO [100], [124]	16	78	Static grasps/ postures	CyberGlove	Raw data (22 DoF)

In this paper we present the KINE-ADL BE-UJI Dataset [218], which contains a total of 1160 recordings with anatomical angles of both hands while performing feeding and cooking activities using a large variety of products. Experiments were performed by 20 healthy subjects while wearing CyberGlove instrumented gloves on both hands, 18 DOF being recorded in each hand at a frequency of 100Hz. The main contribution of this dataset compared to others is the variety of objects used (66 objects), the in-depth study of representative feeding and cooking tasks (58 tasks, divided into 178 actions) and the freedom given to the subjects to perform the tasks. Moreover, the data were collected from both hands, which allows the study of hand coordination. It is also important that the sample of subjects was selected so as to be representative of the healthy adult population (with a controlled proportion of laterality and gender). Furthermore, the data presented is standardized, as it is presented as anatomical angles following the ISB sign criteria [219]. The dataset consists of a Matlab/GNU Octave data structure (*.mat) (provided also in .csv format*) with kinematic data and data about the subjects recruited (age, gender, laterality, weight, height, hand length, hand width and active range of motion (AROM) measured for each DoF). This *.mat* file is accompanied by a guide where information regarding the environment, tasks, objects, data acquisition system and file structure is detailed, thereby allowing the classification of information regarding these parameters (see Appendix III).

4.1.2 Methods

Study participants

The study consisted of two experiments (A and B), with 20 subjects (10 males, 10 females) participating in each experiment. Only 15 subjects participated in both experiments, so that the total amount of subjects recruited was 25. In both experiments, two of the 20 subjects were left-handed. The mean age of subjects recruited was 35.5±7.67 years in experiment A and 38.05±9.52 years in experiment B. The criteria used to select subjects were gender parity in overall data, age between 20 and 65, no reported upper limb pathologies and laterality representative of the overall population (20% of data from left-handed individuals). Before the experiments, all participants gave their written informed consent. All the experiments were performed in accordance with the Ethics Committee of the Universitat Jaume I.

Acquisition setup

Instrumentation. Data acquisition was performed using two CyberGlove (CyberGlove Systems LLC) instrumented gloves (CyberGlove II on the right hand and CyberGlove III on the left hand) connected to a laptop. Each of these gloves has 18 strain gauges that allow the anatomical angles of the underlying joints to be determined. The angle rotated by each joint with respect to the reference posture (hands resting flat on a table, with the fingers and thumb close together, and the middle fingers aligned with the forearms) is then calculated from these signals, according to a previously validated calibration protocol [23]. Furthermore, all the experiments were recorded on video, so as to be able to check the performance of the task when subsequently required.

Environment. The tasks were performed in a laboratory, within an environment that simulated a kitchen (Figure 4.1.1), composed of: a refrigerator (Scenario 1), a high cabinet (Scenario 2), shelves (Scenario 3), a small worktop (Scenario 4), a sink and a rubbish bin (Scenario 5), a large worktop (Scenario 6), a low cabinet with a drawer in its upper part and shelves in the lower part, which has a door (Scenario 7), a table and a chair (Scenario 8) and an oven (Scenario 9).

Objects. A total of 66 objects were used to perform the tasks in the experiments (further information regarding their characteristics can be found in the guide attached to the dataset). The objects were chosen so as to be representative of those most commonly used in cooking and feeding tasks, and were checked to ensure they covered the cooking and feeding objects from the *Yale-CMU-Berkeley Object and Model Set* [125], proposed by Calli *et al*. Some of the objects used were not real, in order to prevent the gloves from getting stained or wet. For example, the eggs to be broken had been previously emptied through a small hole made in the shell. All liquids were replaced by water, and materials such as flour or sugar that could have stained the gloves were replaced by durum wheat semolina. Pieces of polystyrene or cardboard were used to simulate biscuits, bread or crisps. The initial location of the objects in each scenario can be found in the detailed guide attached to the database. Figure 4.1.2 shows an overview of the objects used.

Acquisition protocol

The main dimensions of the hands were measured before helping the subject to put on the instrumented gloves following the manufacturer's instructions. Participants were given clear instructions about how to perform the task, and they were told to start and end each task in the same posture: hands lying relaxed at both sides of the body for tasks performed in a standing posture, and hands lying relaxed on the table when sitting. While carrying out each task, the operator marked (or labelled) the time stamp of some specific events (using the glove software) that were later used to separate different phases or actions.

Figure 4.1.1: Different scenarios of the experiment. Scenarios: Refrigerator (1), high cabinet (2), shelves (3), small worktop (4), sink and a rubbish bin (5), large worktop (6), low cabinet with a drawer in its upper part and shelves in the lower part (7), a table and a chair (8), and an oven (9).

Figure 4.1.2: Overview of the objects used during the experiments. Objects labelled as in the guide attached to the dataset.

Recorded tasks. Two experiments (A and B) were performed. In experiment A, the activities performed were: preparing and having breakfast, baking a cake and cooking omelets. In experiment B, the activities were: setting the table, clearing the table and washing the dishes, making coffee and preparing a simple meal, considering the whole process of performing each task (taking the products from the different scenarios, transporting them, opening/using them and, in some cases, putting them back in their place). Furthermore, all these tasks were separated into different recordings (e.g. using the toaster or pouring and drinking milk), and these recordings were also separated into different elementary tasks (e.g. object grasping, manipulation such as opening tins/jars/bottles, transportation of objects, pouring liquid/solid substances, eating/drinking and other relevant actions). Therefore, experiment A was divided into 33 recordings and experiment B consisted of 25 (a description of all the recordings can be seen in Table 4.1.2 and Table 4.1.3). Further information regarding the elementary tasks considered in each recording can be found in the guide attached to the dataset.

Some of the recordings were performed with the subject standing and others while sitting on a chair (as specified in Table 4.1.2 and Table 4.1.3). Only the eating or drinking activities were simulated, by just bringing the food close to the mouth, and this has been indicated in the task description. The rest of the tasks were performed with realistic objects, and subjects were free to perform the tasks in the way they preferred.

Table 4.1.2: Recordings in experiment A, where R is the ID number of the recording (100 onwards belong to experiment A), and S indicates whether the activity was performed sitting (x) or not.

R	S	PREPARING AND HAVING BREAKFAST
101		Using a toaster.
102		Setting the table: placing the toast.
103		Setting the table: placing a box of biscuits, a carton of milk and an apple.
104		Setting the table: placing a jar of jam, a tub of butter, a mug and a glass.
105		Setting the table: placing a spoon and a knife and sitting on the chair.
106	x	Pouring and drinking milk.
107	x	Dipping a biscuit in milk and eating it.
108	x	Pouring and drinking juice.
109	x	Spreading butter on toast.
110	x	Spreading jam on toast and eating it.
111	x	Eating (simulated) the apple.
		PREPARING, BAKING AND EATING A CAKE
112		Carrying utensils and ingredients to the worktop: a bowl, a carton of eggs and a lemon.
113		Carrying ingredients to the worktop: a jar with flour in it, a bag of sugar and a box of baking powder.
114		Carrying utensils and ingredients to the worktop: a carton of milk and a glass.
115		Breaking an egg into a bowl and throwing the eggshell into the bin.
116		Beating the egg with a fork.
117		Filling a glass with sugar.
118		Grating a lemon.
119		Filling a glass with flour.
120		Opening a carton of milk with scissors and pouring milk.
121		Pouring baking powder into the bowl.
122		Using a mixer to mix the ingredients for the cake dough.
123		Pouring the cake dough onto the baking tray and using a spatula.
124		Putting the baking tray into the oven. Taking the baking tray out of the oven.
125		Cutting a piece of cake with a knife and eating it (simulated).
126		Putting the spatula, the knife, the bowl, the glass and the grater in the sink.
127		Carrying the carton of eggs, the lemon and the carton of milk back to the fridge.
128		Carrying the jar of flour, the bag of sugar and the baking powder to the shelves.
129		Putting the tray with 3kg of food on it into the oven. Taking the tray out of the oven.
		PREPARING OMELETS
130		Beating an egg and salting it.
131		Preparing the pan for cooking on the hob.
132		Cooking and serving a small omelet.
133		Cooking, serving and cutting a big omelet.

Table 4.1.3: Recordings in experiment B, where R (200 onwards belong to experiment B) is the ID number of the recording and S indicates whether the activity was performed sitting (x) or not.

R	S	SETTING THE TABLE
201		Putting a tablecloth on the table.
202		Placing a dish, a glass, a fork, a knife and a napkin.
203		Placing a jug of water, an oil cruet, a salt-shaker and a bowl.
		CLEARING THE TABLE AND WASHING THE DISHES
204		Putting the glass, the jug, the oil cruet and the salt-shaker back in their place.
205		Throwing the leftovers on the plates into the rubbish bin.
206		Throwing the leftovers in the bowls into the rubbish bin.
207		Removing the tablecloth from the table and folding it.
208		Washing the glass, the bowl, the dish, the fork and the knife.
209		Putting the glass, the bowl, the dish, the fork and the knife back in their place.
210		Cleaning the worktop.
		PREPARING AND DRINKING COFFEE
211		Taking a jar of ground coffee and opening it.
212		Filling the filter handle of the coffee machine with coffee.
213		Placing a cup under the coffee machine and pressing the power button.
214		Placing the cup of coffee and the sugar pot on a tray. Carrying it to the table.
215		Throwing the used ground coffee into the rubbish bin.
216	x	Adding sugar to the coffee, stirring and drinking it (simulated).
		PREPARING AND EATING A SIMPLE MEAL
217		Pouring crisps from a bag into a bowl.
218		Closing the bag of crisps with a sealing clip.
219		Pouring olives from a tin into a little bowl.
220		Pouring salted biscuits from a jar onto a dish.
221		Setting the table: placing the dish and the bowls.
222		Opening a bottle of wine with a corkscrew.
223		Setting the table: placing a glass of wine. Sitting on the chair.
224	x	Pouring wine and drinking it (simulated).
225	x	Eating (simulated) olives, crisps and biscuits.

Elementary tasks. As mentioned previously, each of the recordings (R) (33 recordings in experiment A and 25 in B) is composed of different elementary tasks. For example, in the activity of having breakfast (consisting of 11 records, as seen in Table 4.1.2) record R=106 (pouring and drinking milk) is composed of four elementary tasks: opening the carton, pouring, closing the carton and drinking (see Table 4.1.4). For an unambiguous identification of each of the tasks, a unique ID was assigned to each elementary task, with a total of 99 elementary tasks in experiment A and 79 in B (178 elementary tasks altogether). All the elementary tasks involved grasping or manipulating a product or element with the hands, except for some cases where the subject moved without handling anything, which were labelled as ”Displacement without manipulation”. For each elementary task, the record considers all time instants since the object was grasped until it was released. In those cases in which the object was released in a specific place or transported to a specific location in the scenario, this location is specified in the description of the elementary task. In all other cases, the release was performed on the surface closest to the subject (table, worktop, etc.).

Table 4.1.4: Elementary tasks into which task R=106 is divided. Columns containing R (ID of the recording), ID (ID of the task), OBJ (ID of the objects used during the task), SCEN (ID of the scenario where the task is performed) and S (marked with an "x" when the task was performed sitting).

R	ID	OBJ	SCEN	S	HAVING BREAKFAST
106	16	51	8	x	Opening the cap of the carton of milk
	17	11, 51	8	x	Pouring milk from the carton into the mug
	18	51	8	x	Closing the carton of milk
	19	11	8	x	Drinking from the mug (simulated)

Active range of motion (AROM). After performing all the experiments, subjects were asked to perform a set of postures [18] in order to measure their AROM of the joints of both hands, which are presented in the *.mat* file, where subject information is also provided.

Signal processing

Angles calculation. Joint angles were calculated from raw data collected according to the calibration protocol proposed in previous works [23]. This protocol includes the determination of gains and also some corrections because of cross-coupling effects for specific anatomical angles. The anatomical angles obtained according to the protocol are those shown in Figure 4.1.3:

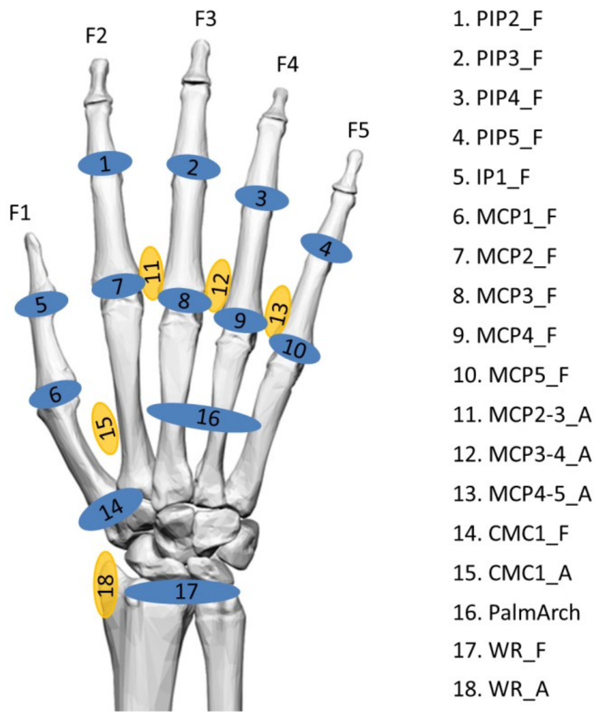


Figure 4.1.3: List of recorded anatomical angles. Nomenclature: _F for flexion (in blue), _A for abduction (in yellow); 1 to 5, digits. Joints: IP for interphalangeal joint, PIP for proximal interphalangeal joints, MCP for metacarpophalangeal joints, CMC for carpometacarpal

joints, PalmArch for palmar arch resulting from flexion/extension of carpometacarpal joints of ring and little fingers, WR for wrist.

Data cutting and splitting. The initial and final instants of each record, in which the hands were static, were trimmed. The records were then separated into the different elementary tasks as detailed in the dataset guide by using the labelling performed by the operator while recording the data. In some specific cases in which labelling data was missing, labelling was performed using the video recordings.

Filtering. All data were filtered with a 2^{nd} order two-way low pass Butterworth filter with a cut-off frequency of 5Hz.

4.1.3 Data Records

Volume of data collected

A total of 3560 elementary tasks were recorded across all the subjects and experiments, with a total duration of the recordings of 7h, 30min and 43 seconds.

Data files

Data are presented as a single Matlab data structure (BE_UJI_DATASET.*mat*), which is composed of two secondary structures (KINEMATIC_DATA and SUBJECT_DATA). KINEMATIC_DATA contains all kinematic data recorded, classified by experiment, record, part and subject, while SUBJECT_DATA contains data of the subjects recruited (age, gender, laterality, weight, height, hand length, hand width and measured AROM). This structure is accompanied by a guide (.pdf), which provides detailed information regarding the data series as well as the environment, tasks, objects and data acquisition system.

Sign criteria

The sign criteria used on each joint movement were defined as follows:

- **PIP(2-5)_F, IP1_F, CMC1_F, MCP(1-5)_F, WR_F:** Flexion + / Extension -
- **MCP(2-3, 3-4, 4-5)_A:** Fingers separated + / Fingers together -
- **PalmArch:** Flexion +/Extension -
- **WR_A:** Ulnar deviation +/Radial deviation –
- **CMC1_F:** Flexion +/Extension – (See Figure 4.1.4)
- **CMC1_A:** Abduction +/Adduction - (See Figure 4.1.4)

Notice that movement of thumb CMC joint is complex, and nomenclature used in literature to define these movements is varied [220], [221]. We adopted the one used by Brand and Hollister [221].

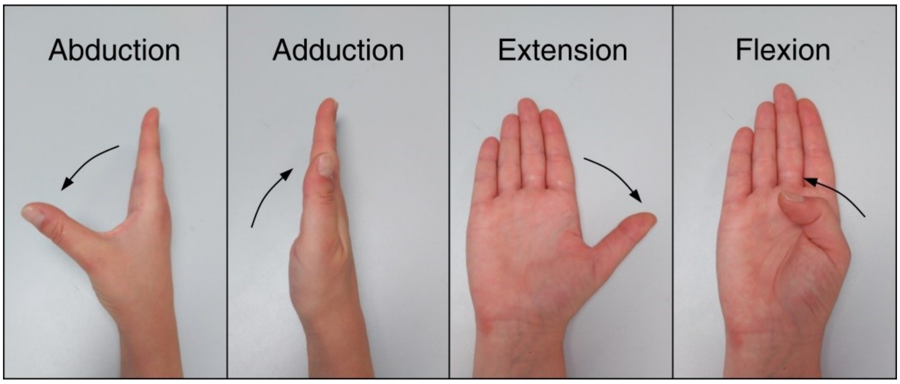


Figure 4.1.4: Movements of the carpometacarpal joint.

4.1.4 Technical Validation

Data acquisition

Before and after carrying out each experiment the subjects were asked to perform movements such as closing their hands or just moving them randomly, in order to make sure that all the gauges were shown to be working on the virtual model of the CyberGlove software.

Furthermore, all tasks recorded were checked in order to ensure that the number of labels used to divide them into elementary tasks was correct and that no labels were missing.

In order to avoid possible unexpected signal values, all data collected were filtered using a 2nd order two-way low pass Butterworth filter with a cut-off frequency of 5Hz, as explained in previous sections.

Comparison of active and functional range of motion for each subject and experiment

The percentiles P95 and P5 were calculated for each hand joint, experiment and subject. Then, for each subject and experiment, a subject-specific functional range of motion (FROM) was computed for each hand joint angle as the P5 and P95 percentiles of all his/her recordings, therefore representing the angles of 90% of the postures performed by the subject during the experiment. These FROMs were compared with the AROMs measured for each subject. Almost all the FROMs were inside the AROMs, except in some cases where the extension of thumb interphalangeal and metacarpophalangeal joints and the index metacarpophalangeal joint extension were higher than the AROM measured (maximum difference reported between FROM and AROM was 25° approx.). This may be attributable to activities that implied a passive extension of these joints while manipulating objects (e.g. cutting with a knife implies a precision grasp with a forced extension of the thumb joints and index interphalangeal joint that is higher than the achievable active extension).

Statistical descriptive analysis of all data collected

With all data collected, box and whisker graphs were plotted and general FROMs were calculated. Then, the extreme values of all the subjects' AROMs calculated previously were taken to calculate general AROMs. When general FROMs and AROMs were compared, most values of the FROMs were between those of the AROMs, which supports the veracity of the data. Nevertheless, some outliers were higher than those values (Figure 4.1.5), especially in extension of CMC1, MCP2, PIP2 and PIP3 and flexion of right PIP2 to PIP5. This can also be attributable to activities that implied a passive flexion/extension of joints while manipulating, as mentioned before. It has to be emphasized that the FROMs of PIP2 to PIP5 were higher than the AROMs only for the right hand, which is the dominant hand of most subjects.

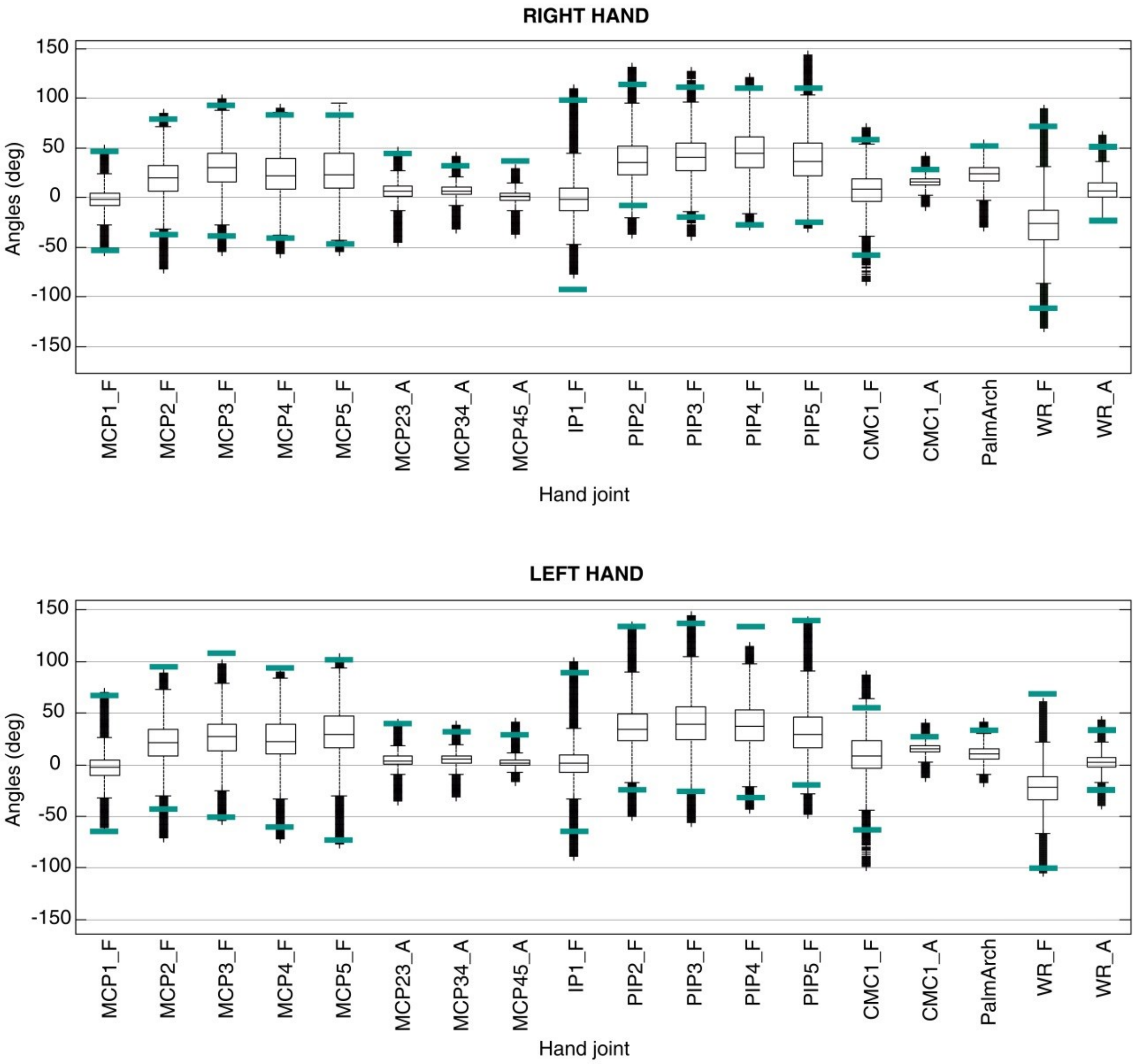


Figure 4.1.5: Comparison of maximum AROMs and FROMs. Box and whisker plots for general FROMs, general AROMs are marked with green lines. Unmarked AROMs were not measured. Joints and movements labelled as explained in Figure 4.1.3.

Limitations

The use of instrumented gloves may imply some loss of dexterity during the performance of fine manipulation tasks. Nevertheless, this loss of dexterity may not have a significant effect on the ranges of motion, mean postures or movement synergies.

4.1.5 Usage Notes

These data can be used for several applications, from machine learning purposes to product design. The main strengths of this dataset for these potential uses are the motion capture characteristics (validity of the motion capture system, anatomical joints measured and frequency of acquisition), the structure of the data presented (*.mat*, which allows easy data handling), the variety of objects used (different shapes and weights) and the wide range of cooking/feeding tasks considered.

It has to be taken into account that real food or drinks were not used to perform the tasks in order to prevent the gloves from getting stained or wet (all products are appropriately tagged with the corresponding substitutive material in the dataset guide file). Therefore, tasks involving these elements were simulated and might be performed in a slightly different way than when performed with real food/drink.

Even though tasks and products of this dataset were selected to be representative of the different cooking and feeding tasks, some specific tasks or objects involving fine motor skills were discarded because of the loss of manipulation dexterity that the use of instrumented gloves implied (e.g. opening the thermally sealed plastic layer of precooked food packaging). Some wrist angles are also missing because of improper fitting of the wrist sensors to some subjects' hands.

Finally, velocity of performance of the tasks might be slightly affected by the loss of dexterity and touch sensitivity resulting from the use of the instrumented gloves.

4.2 An analysis of hand kinematics in feeding and cooking tasks

The work presented in this section is being prepared to be submitted to the international journal Human Movement Science.

4.2.1 Introduction

In a previous section (section 4.1, Chapter 4), the KINE-ADL BE-UJI dataset has been presented [222], containing a total of 1160 recordings with anatomical angles of both hands from 20 healthy subjects while performing feeding and cooking ADLs using 66 objects in a natural way. As explained previously, this dataset was tailored to be representative of the tasks and products of feeding and cooking ADLs. Its main aim is to provide useful hand kinematic data to the research community for several purposes such as clinical assessment, product design or prosthetics development. In this chapter, this dataset is used for providing an overview of the kinematic requirements during product manipulation in feeding and cooking ADLs.

As observed in section 2.2.5 (Chapter 2), several works have already studied human hand kinematics during ADLs and product manipulation with different purposes, providing relevant data of functional requirements. Nevertheless, most o works analysed only specific tasks/products and/or focused on specific postural parameters such as FROM or synergies, among others, usually neglecting non-dominant hand and velocity-related hand joint parameters.

Analysing and providing descriptive values of postural kinematic parameters during the performance of tasks, such as median or extreme postures, may help to reveal which are the tasks that require more extreme postures. Furthermore, the analysis of velocity-related parameters, such as median or peak velocities, may provide indicators of the level of dexterity/manipulation ability required to perform a given task, as some literature reviews of measures of dexterity and hand function tests observed that 20% of these tests assessed speed and quality of movement, 10% just quality of movement, and 70% just velocity [223]. Moreover, descriptive data of both postural and velocity-related parameters obtained from a representative sample of healthy subjects while developing representative ADLs can be also used as normative data for clinical assessment. In particular, velocity-related parameters while performing precision manipulation tasks have been demonstrated to have enough test-retest reliability to be used as clinical assessment measures [224]. All these indicators may help to reveal the tasks that are more difficult to be performed by people with pathologies affecting hand function. This information will be helpful to identify those tasks for which developing assistive devices or universal design solutions would be worthy.

The importance of considering both a wide variety of tasks and products for identifying hand kinematics requirements lies in the outcomes of different works that claim the dependency of hand kinematics on the task performed and the product's characteristics, as observed in section 2.2.5 (Chapter 2). Nevertheless, the large number of products used and tasks performed even within the specific field of cooking and feeding presented in the KINE-ADL BE-UJI dataset (which are key for personal autonomy), hinder the analysis. Classifying ADLs according to different task features might help to analyse the data by mapping the mobility requirements according to task characteristics.

Classifying ADLs is not straightforward. Many activities require using several grasp types while manipulating products, making it difficult to classify the tasks using only grasp type taxonomies. Some works in the literature have used product characteristics such as shape or orientation in order to classify tasks [135]. Nevertheless, owing to the variety of product shapes and the freedom given to participants of the KINE-ADL BE-UJI dataset when grasping products, this classification would require a very time-consuming process of visual analysis of videos. Fortunately, as observed in section 2.2.3 (Chapter 2), some authors have already tried to face this gap in grasp taxonomies to classify ADLs, proposing extended grasp taxonomies with features related to the grasping action, such as intended motion or force type used [12]. These features might help to characterise ADLs in a more general way and, at the same time, provide significant information about the tasks performed.

Thus, this chapter aims to contribute to widen the knowledge regarding functional requirements during feeding and cooking tasks, by characterising healthy hand behaviour, providing normative data of quantifiable kinematic parameters of both hands while performing a wide variety of feeding and cooking ADLs. The tasks considered are those presented in the KINE-ADL BE-UJI Dataset, which are classified according to different aspects, such as the force type and the intended motion. Descriptive analyses of posture and velocities are presented by task and/or groups of tasks, and main findings are discussed.

4.2.2 Methods

Task groups

As mentioned in the Introduction section, tasks considered were all the 178 *elementary tasks* from the KINE-ADL BE-UJI Dataset, a publicly available dataset published by the B&E Research Group (see section 4.1, Chapter 4). The tasks were grouped by the basic task performed (drinking, eating, etc.), and then by similarity in the force type and the intended motion required, according to the Liu et al. grasp taxonomy. In this taxonomy they defined the intended motion as the attitude toward bodily tension and control, which can be *free*, *bound* or *half-bound*. While *free* refers to a very casual movement direction, *bound* refers to a very stiff and tightly controlled action. On the other hand, the force type taxonomy they presented was composed of twenty verbs from the English language that they considered that provided a clear description of the grasping actions: break off, extend, grab, hold, lever, lift, place, press, pull, pinch, put in, roll, rub/stroke, scratch, squeeze, take out, throw, turn, twist and swing.

All the elementary tasks from the dataset were classified into a total of 13 task groups, which are presented and described in Table 4.2.1, along with their task group ID, the number of tasks belonging to each group, the force types and the intended motions of the tasks of the group. The list of tasks belonging to each group are detailed in Tables AIV.1 to Table AIV.13 of Appendix IV. Five tasks were considered as belonging to two different groups, because of the complexity of those tasks, combining different actions, each of them matching the features of different groups (e.g.: *Taking a bottle of oil from the worktop, opening the cap, pouring oil into the pan, closing the bottle and leaving the bottle on the worktop* was considered both in G4 (O*pening and closing packages: other*) and in G7 (*Pouring*)).

Table 4.2.1: Task groups considered in the analyses, along with the number of tasks considered in each group, force type and intended motion. Force type "lift-" (added by the authors to the original Liu et al. grasp taxonomy) indicates the lifting action when grasping an object from a surface.

ID	TASK GROUP	DESCRIPTION	FORCE TYPE	NUMBER OF TASKS	INTENDED MOTION
G1	Transp.: open space	Transportation of objects from shelf, table or worktop.	Hold, lift, place, lift-	32	Free motion
G2	Transp.: closed space	Transportation of objects from cabinet, freezer or drawer.	Hold, lift, place, put in, take out, pull, press	31	Free motion / Half bound / bound
G3	Opening and closing packages: unscrewing and screwing	Unscrewing and screwing caps.	Grab, hold, twist, place, lift-	6	Bound
G4	Opening/ closing packages: tearing, pulling, etc.	Opening/closing packages that require pulling (such as bags of chips), pushing, tearing, etc.	Break off, grab, hold, press, pull, take out, place, lift-	22	Free motion / Half bound
G5	Eating	Eating meals that are held within the hand: apples, biscuits, etc.	Hold, place, lift-	7	Free motion
G6	Drinking	Drinking from several recipients.	Hold, place, lift-	4	Free motion
G7	Pouring	Pouring substances from a recipient to another.	Hold, place, grab, lift-	18	Free motion
G8	Using cutlery and kitchen utensils	Using cutlery and utensils such as a corkscrew or a spatula.	Hold, place, rub, extend, press, pull, twist, grab, take out, lift-	21	Free motion / half bound / Bound
G9	Using appliances	Using appliances such as a mixer or a coffee machine.	Break off, grab, hold, place, pull, press, punch, put in, take out, twist, lift-	11	Free motion / half bound / Bound
G10	Cleaning	Tasks such as washing the dishes or cleaning the worktop.	Grab, hold, lift, place, pull, press, put in, rub/stroke, squeeze, lift-	7	Free motion / Half bound
G11	Opening and closing cabinets, drawers and moving chairs	Isolated tasks of opening and closing cabinets and drawers and pushing and pulling chairs.	Push, pull	5	Half bound / bound
G12	Displacement without manipulation	Free hand motion while moving around the scenario without holding any object or performing any specific task.	Swing	8	Free motion
G13	Other	Tasks that did not match the characteristics to be considered into any specific group of tasks.	Grab, hold, place, press, rub, throw, lever, lift-	11	Free motion / half bound / Bound

Data analyses

In order to better interpret data, analyses were performed considering both hands data, but selecting only the recordings of right-handed subjects (18 subjects), as some left-handed subjects used to perform some tasks with their non-dominant hand. The full recordings as presented in the dataset were considered, without trimming resting periods, in order to be representative of bimanual ADLs, where sometimes the non-dominant hand does not participate in the task. The instant velocity was computed from these kinematic data selected, which were already presented filtered in the dataset. For each subject, task and joint angle, seven parameters were computed: median posture along with 5th and 95th percentiles of the posture, median and 95th percentile of positive velocities (flexion and abduction of fingers and thumb, flexion and ulnar deviation for wrist, according to the sign criteria considered), and median and 5th percentile of negative velocities (extension and adduction of fingers and thumb, extension and radial deviation for wrist) Additionally, the percentage of time that joint velocity was above 10 deg/s (henceforth, manipulability index) was computed as indicator of the level of manipulability of the task for each subject, task and joint. Furthermore, to better analyse the global manipulability of all the joints in bimanual manipulation, the percentage of time that at least one joint per hand presented velocity above 10deg/s was computed (henceforth, global manipulability index). It was calculated for right and left hands separately, and then considering both hands. Data are presented in box and whiskers plots per hand joint and task group.

4.2.3 Results

Box and whiskers plots of the parameters calculated for each subject, task and joint are presented in Figures 4.2.1 to 4.2.8, distinguishing by task group: median and peak angles in Figures 4.2.1 to 4.2.3, median positive and negative velocities in Figures 4.2.4 and 4.2.5, and peak positive and negative velocities in Figures 4.2.6 and 4.2.7, respectively. The manipulability index is presented in Figure 4.2.8, and the global manipulability index in Figure 4.2.9. Sign criteria used and joints labelled as described in section 4.1. Plots were created using IBM SPSS software, where the box represents the interquartile (IQ) ranges which contain the middle 50% of the records. The whiskers extend to the highest and lowest values which are no greater than 1.5 times the IQ range. The line across the box indicates the median. Outliers (dots) are cases with values between 1.5 and 3 times the IQ range (beyond the whiskers).

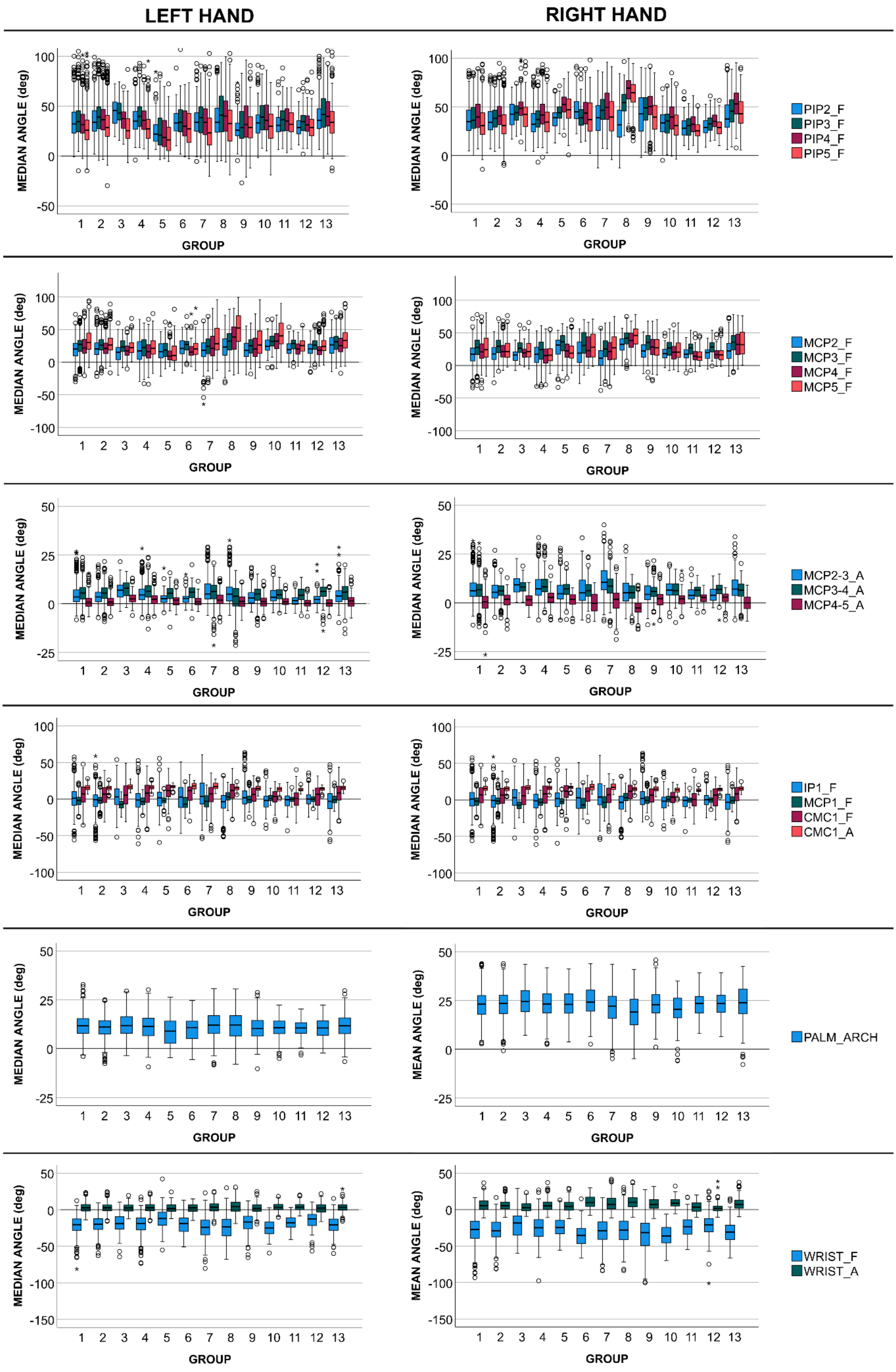


Figure 4.2.1: Box and whiskers plot of median angles (deg) while performing tasks from each group.

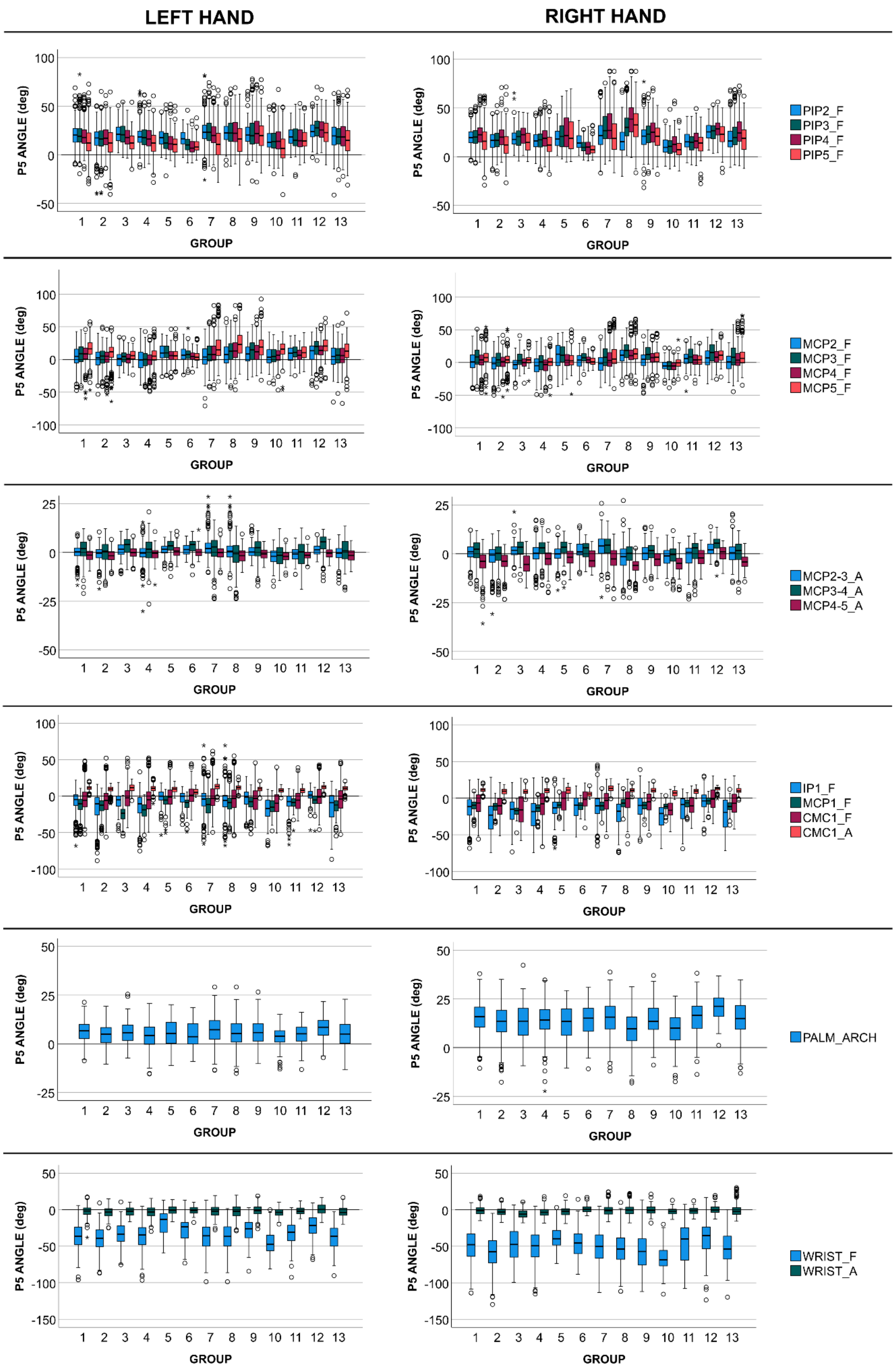


Figure 4.2.2: Box and whiskers plot of 5th percentile of the posture (abbreviated as P5 angle) (deg) while performing tasks from each group.

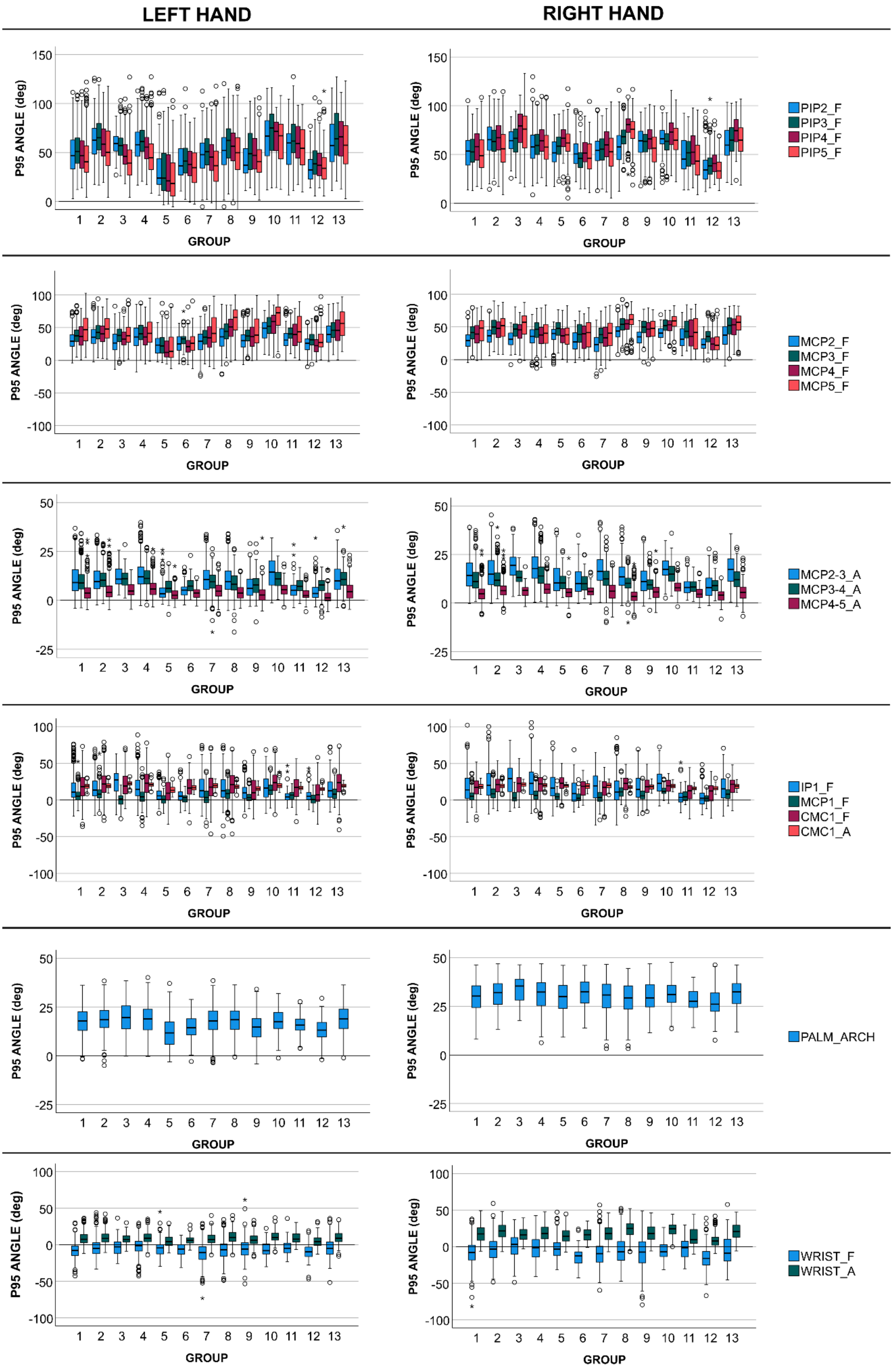


Figure 4.2.3: Box and whiskers plot of 95th percentile of the posture (abbreviated as P95 angle) (deg) while performing tasks from each group.

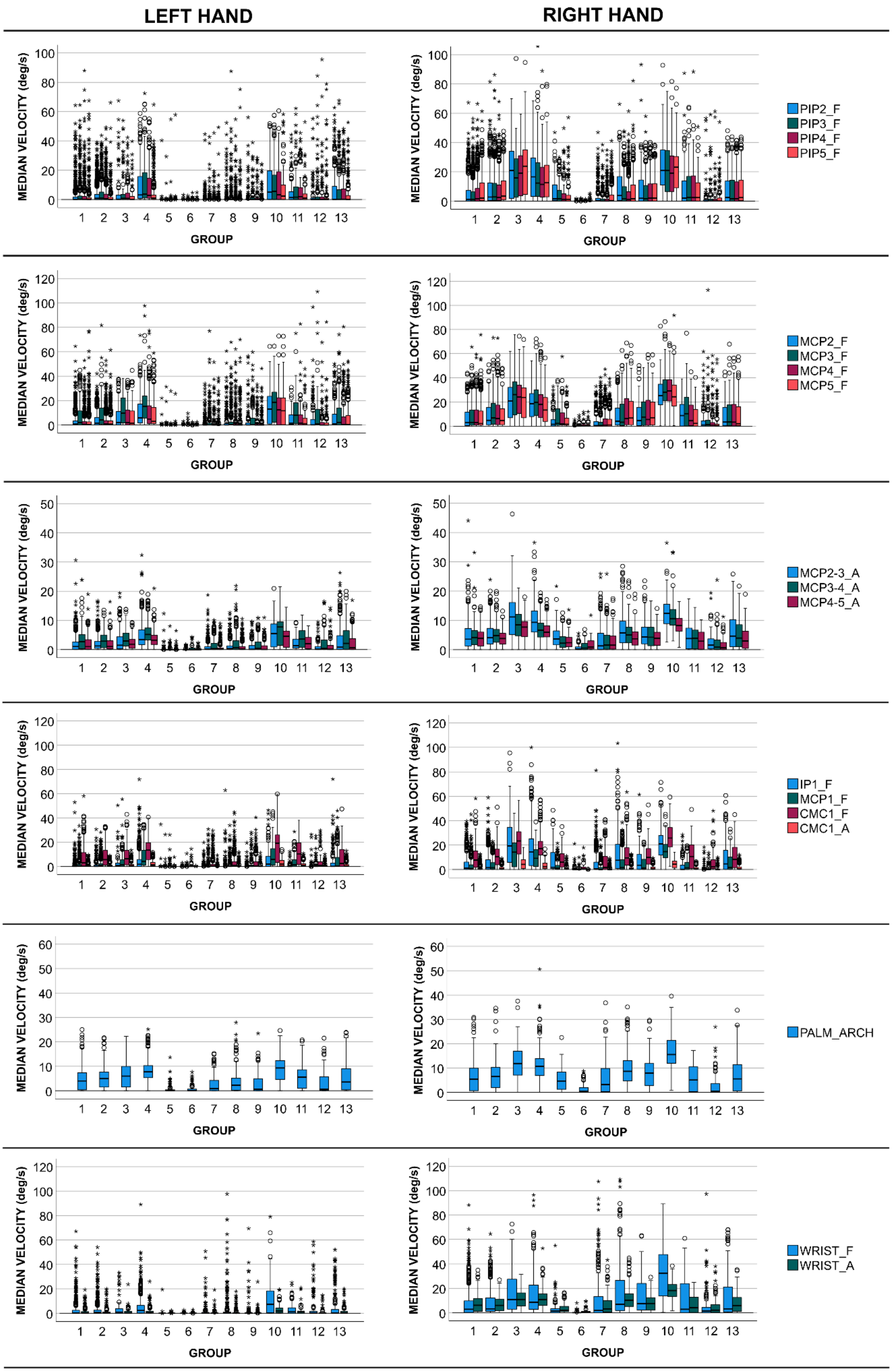


Figure 4.2.4: Box and whiskers plot of median positive velocity (deg/s) while performing tasks from each group. Positive velocities correspond to flexion and abduction of fingers and thumb, and flexion and ulnar deviation for wrist.

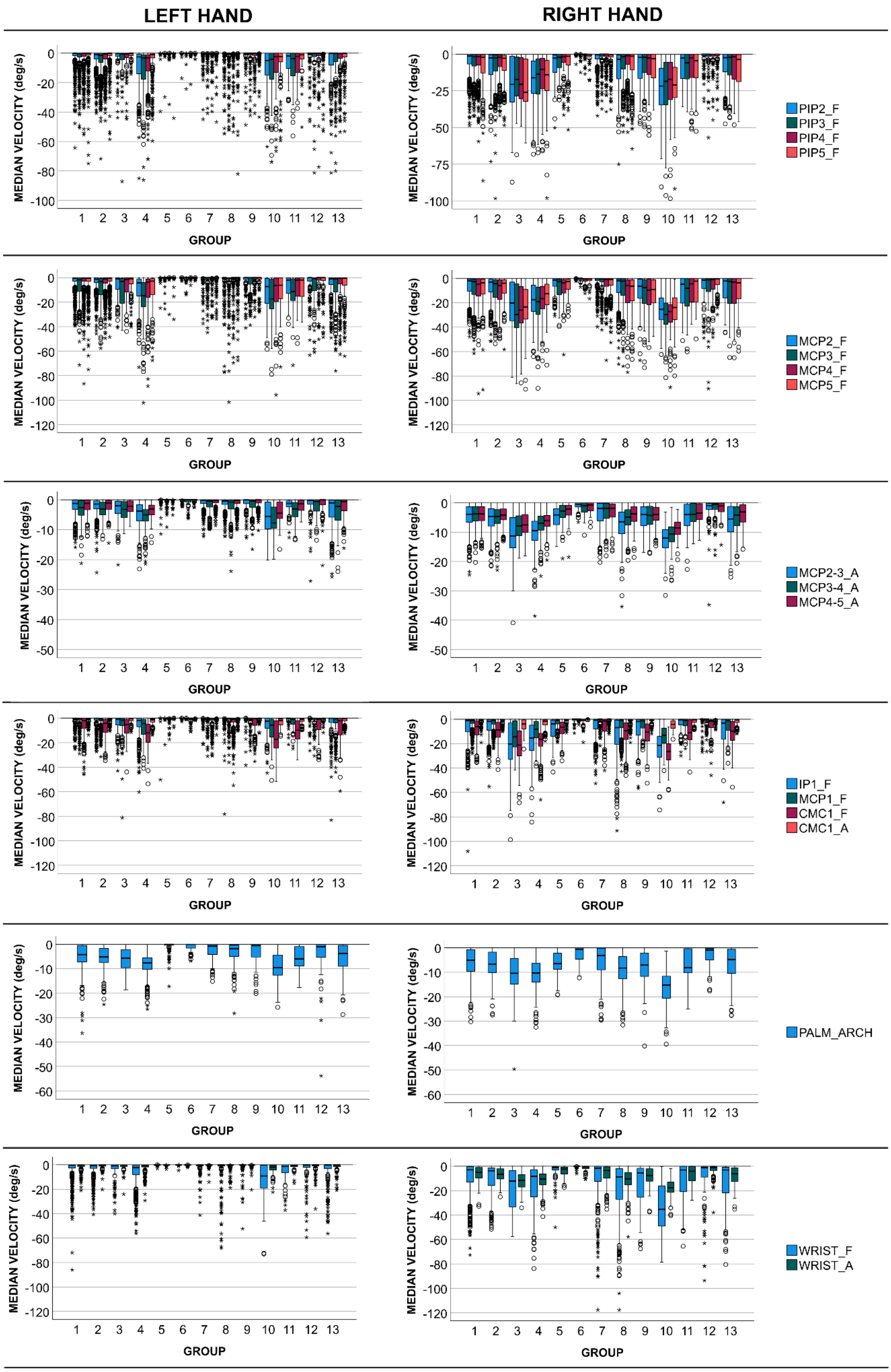


Figure 4.2.5: Box and whiskers plot of median negative velocity (deg/s) while performing tasks from each group. Negative velocities correspond to extension and adduction of fingers and thumb, and extension and radial deviation for wrist .

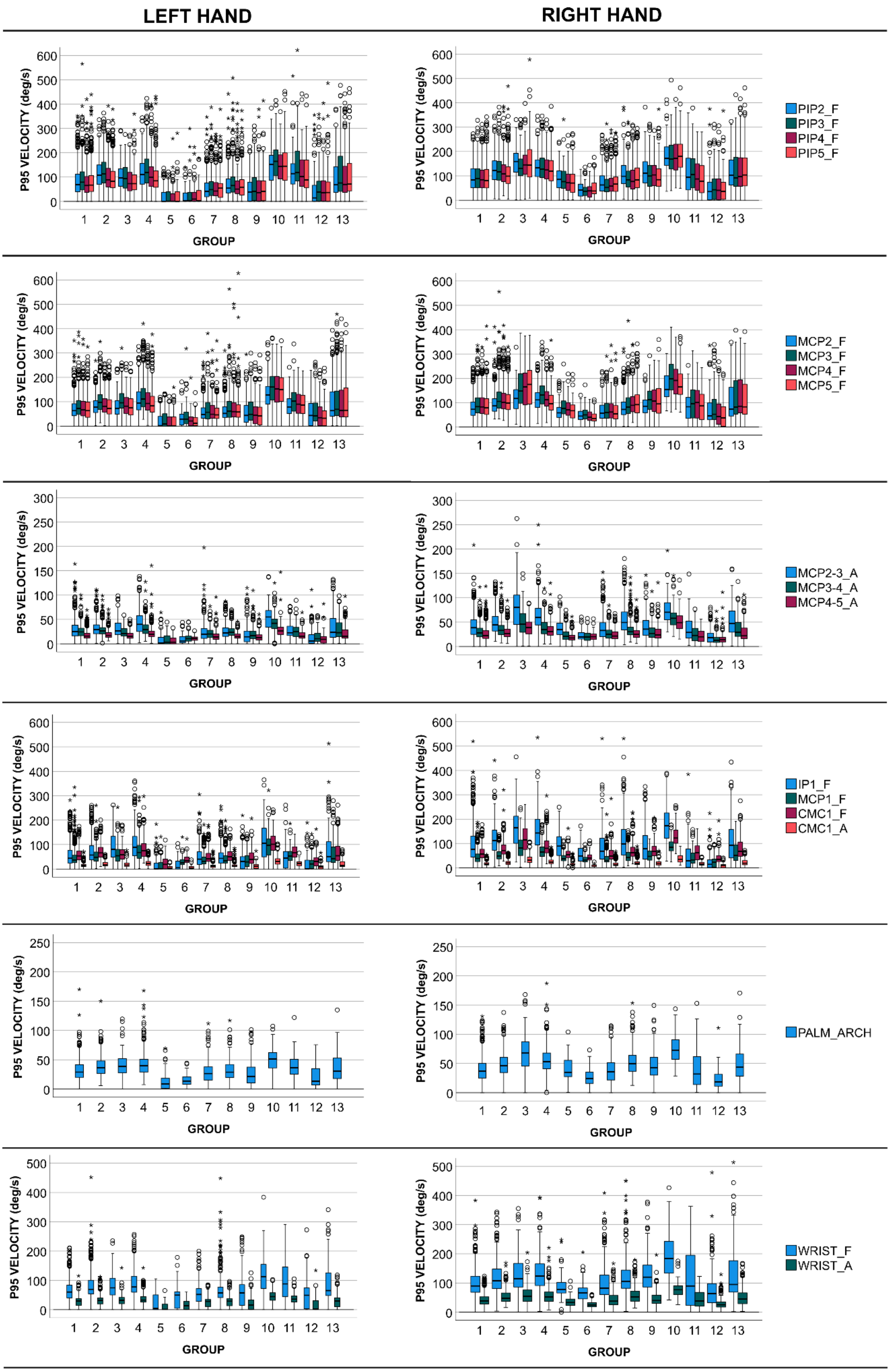


Figure 4.2.6: Box and whiskers plot of 95th percentile of positive velocity (abbreviated as P95 velocity) (deg/s) while performing tasks from each group. Positive velocities correspond to flexion and abduction of fingers and thumb, and flexion and ulnar deviation of wrist.

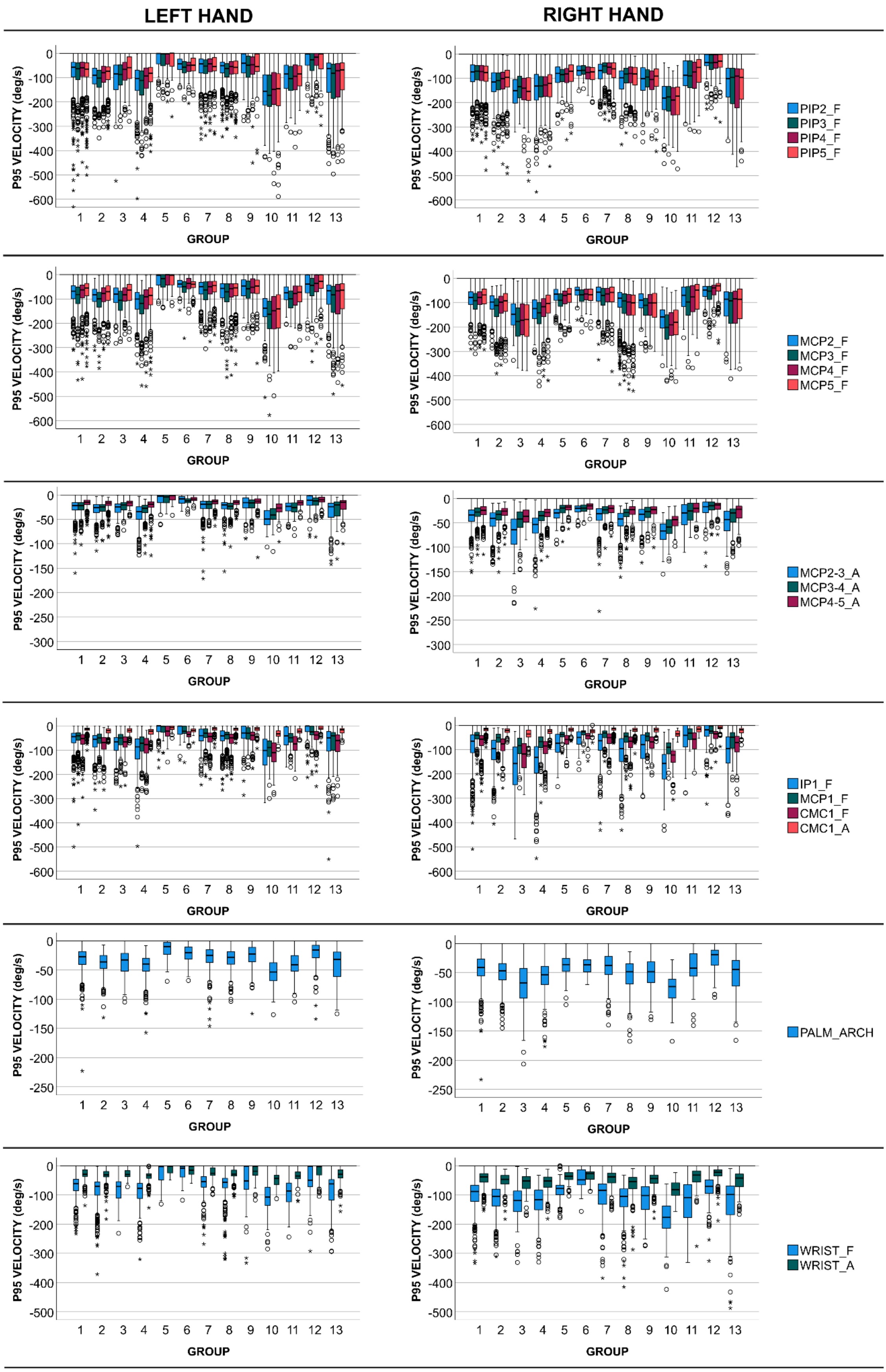


Figure 4.2.7: Box and whiskers plot of 95th percentile of negative velocity (abbreviated as P95 velocity) (deg/s) while performing tasks from each group. Negative velocities correspond to extension and adduction of fingers and thumb, and extension and radial deviation of wrist.

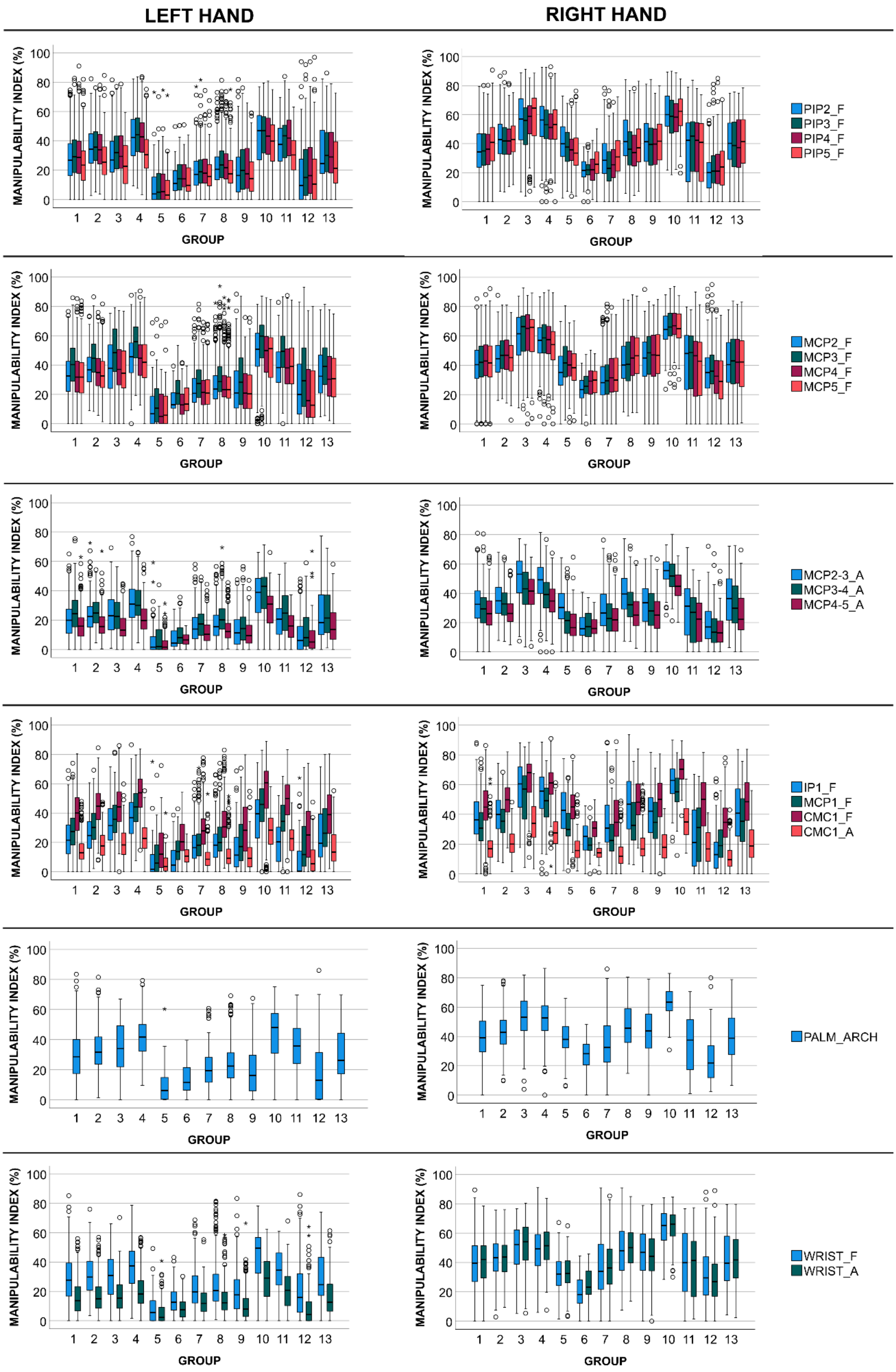


Figure 4.2.8: Box and whiskers plot of the manipulability index measured as the percent of time with joint velocities above 10 deg/s while performing tasks from each group.

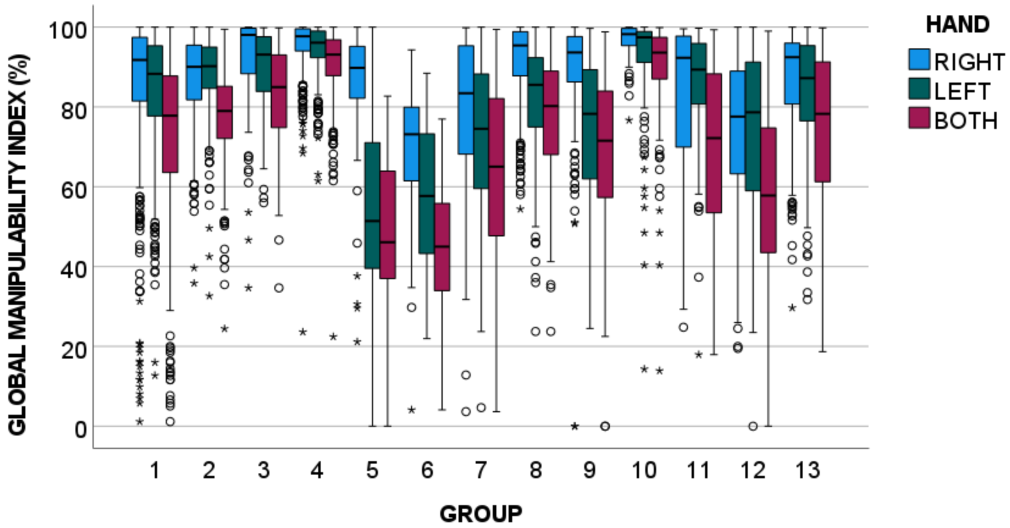


Figure 4.2.9: Box and whiskers plot of the index of global manipulability index measured as the percent of time with at least one joint per hand with velocities above 10 deg/s while performing tasks from each group. Blue: Global index of staticity considering all right hand joints. Green: Global index of staticity considering all left hand joints. Red: Global index of staticity considering all both hands joints

4.2.4 Discussion

The results are discussed along the following sections separately by degrees of freedom, starting with flexion of fingers (PIP and MCP joints from index to little) and followed by finger abductions, thumb motion, palmar arching and wrist motion. In each section, the observed effects on kinematic parameters are related to task group characteristics. Characteristics requiring more extreme postures or higher velocities are then identified, along with extreme values observed. In order to assess the relevance of the extreme postural values found, they are compared to the active ranges of motion (AROMs). A section discussing the manipulability requirements of the different task groups is also presented, by means of considering the data from both the individual manipulability index of each hand joint and the global manipulability index. Finally, a compendium section is presented, summarizing all the kinematic parameter values that may be problematic for hands with reduced function.

Analysis of kinematic parameters by degrees of freedom

Flexion of fingers

A median flexion above 25° is required in PIP and MCP joints of both hands in almost all the task groups (Figure 4.2.1), with flexion generally lower in the left hand. PIP median flexion was higher than the MCP one, presenting also more variability. The less flexed postures of right hand correspond to groups G11 (opening/closing cabinets, drawers and chairs) and G12 (displacement without manipulation). Contrarily, the most flexed postures correspond to group G8 (using cutlery and kitchen utensils), with median flexions over 50° in middle, ring and little finger PIPs, which is probably due to the small diameter of cutlery and kitchen utensils. Nevertheless, the index finger does not present such large flexion values in that group, as an intermediate grasp is used for cutlery and kitchen utensils, where index is extended (Figure 4.2.10). When analysing extreme values (5th and 95th percentile angles) (Figure 4.2.2 and Figure 4.2.3, respectively), the tasks with highest flexion are those from G3 (opening and closing packages: unscrewing and screwing), G8 (using cutlery and kitchen utensils), G10 (cleaning) and G13 (other), presenting median values of the 95th percentile posture all over 50º in PIP joints and 25º in MCP, presenting high variability in PIP joints, being remarkable the variability of little PIP in G3 (opening and closing packages: unscrewing and screwing), going from 20º to 140º, approximately, flexion hardly achievable even for healthy hands. Contrarily, G1 (transportation: open space), G2 (transportation: closed space), G4 (opening and closing packages: other) and G9 (using appliances) and G11 (opening/closing cabinets, drawers and moving chairs) present several extension outliers, being some of them above 45º for index MCP and above 25º for PIP joints. These outliers are not problematic in healthy hands, as they are within the AROMs of the subjects recruited to create the dataset, but may be problematic when hand mobility is reduced. These outliers correspond mainly to tasks where large objects are manipulated or a pushing action is performed such as taking the spatula, the knife and the bowl from the worktop and putting them in the sink (G1), carrying the jar of flour (G1), opening the jar of flour (G4), switching the hob on (G9) or sitting in the chair at the table (G11).

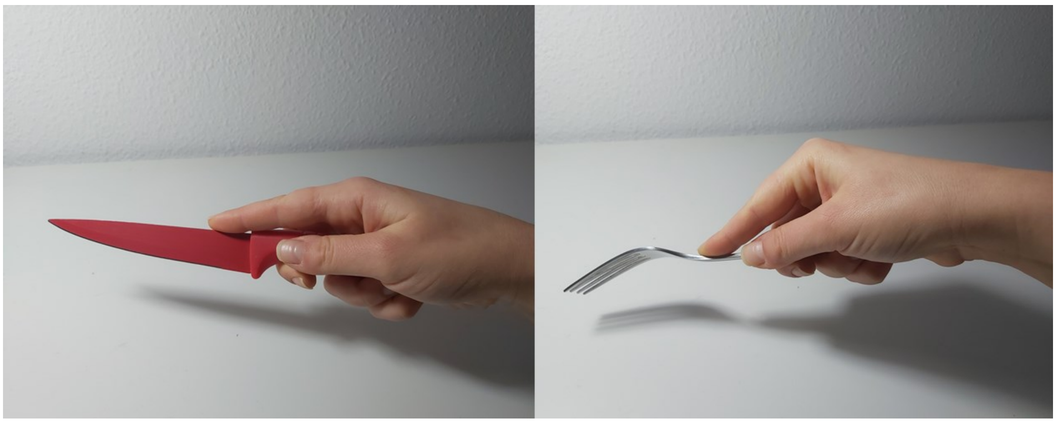


Figure 4.2.10: Intermediate grasps performed when using cutlery and kitchen utensils, with index finger extended.

Median positive and negative velocities in the right hand (Figure 4.2.4 and Figure 4.2.5, respectively) are similar. There are three groups with remarkably higher median velocities, with median values of the median velocity above 10deg/s in all the joints in G4 (opening and closing packages: other), and above 15deg/s in PIPs and 20deg/s in MCPs in G3 (opening and closing packages: unscrewing and screwing) and G10 (cleaning). Peak positive and negative velocities are also over 100 deg/s in G3 (opening and closing packages: unscrewing and screwing) and G10 (cleaning). Nevertheless, there are three groups where median velocities obtained are close to zero: G6 (drinking), G7 (pouring) and G12 (displacement without manipulation). This is obviously attributable to the fact that static grasps are performed in the task groups where lowest velocities have been observed, while more precision manipulation is needed in the ones with highest velocities.

Flexion of fingers of the left hand (Figure 4.2.1) did not present important variations among groups, because as a non-dominant hand, it was commonly holding or supporting objects in most of the tasks, while the main manipulation was being performed by the dominant hand. G5 (eating) presents median values under 25º, as in the tasks of this group (which do not involve using cutlery) subjects rarely used their non-dominant hand, which it is just resting on the table (if sitting) or hanging relaxed (if standing). The only groups that present slightly higher MCP median flexion values are G7 (pouring), G8 (using cutlery and kitchen utensils) and G10 (cleaning), as the majority of these tasks are bimanual, even the pouring ones (G7), where usually the non-dominant hand is holding a recipient. The highest extreme flexions (95th percentile) are obtained in tasks from G10 (cleaning), which also presented high flexion in right hand, presenting median values of the 95th percentile flexion above 70º for PIP and 50º for MCP. These results are consistent with the tasks performed in G10, where different objects presenting different shapes and sizes (dishes, bowls, glasses, cutlery, etc.) are manipulated with both hands, sometimes using two objects simultaneously, and several tasks (cleaning with the sponge, drying with a towel, putting objects into the cabinet) are performed, leading to different grasp types and manipulation within hands with no static grasps. Furthermore, when analysing 5th percentile postures, some extension outliers are observed in groups G1 (transportation: open space), G2 (transportation: closed space), G4 (opening and closing packages: other). Outliers in these task groups were also observed in right hand, as previously mentioned, being above 25º in PIP and 50º in MCP, which may not be problematic for healthy hands but it would for pathological ones, as they are quite close to the measured AROMs.

Velocities in the left hand (Figure 4.2.4 and Figure 4.2.5, respectively) are lower than the ones observed in the right hand. This is attributable, again, to the fact that this hand is commonly holding the objects while tasks are being performed by the dominant hand. The groups with higher positive and negative median velocities were G4 (opening and closing packages: other) and G10 (cleaning), what is attributable to the precision bimanual manipulation performed in these task groups, the variety of products, force types and intended motion of the tasks. Remarkably high peak positive and negative velocities are also found in G10 (cleaning).

Finger abductions

Finger abductions (Figure 4.2.1) present similar median values for both hands, being almost all median values between 0º and 10º. Index-middle and middle-ring abductions present similar mean values, but variability of index-middle abduction is quite higher. Ring-little abduction is generally low. E.g., median value is below 0º in G8 (using cutlery and kitchen utensils), as a consequence of the superposition of both fingers in the intermediate grasp performed when holding cutlery and kitchen utensils. No significant differences in finger abductions are found between groups when observing 5th and 95th percentile abductions (Figure 4.2.2 and Figure 4.2.3). Outliers of extreme abductions were isolated values and no higher than 45º for index-middle abduction and 40º for middle-ring abduction, which is quite close to the measured AROMs.

Median and peak positive and negative velocities of the right hand (Figure 4.2.4, Figure 4.2.5, Figure 4.2.6 and Figure 4.2.7) are higher for the index-middle abduction, because of its important role in precision manipulation. Generally, right hand velocities are higher in groups G3 (opening and closing packages: unscrewing and screwing), G4 (opening and closing packages: other) and G10 (cleaning), owing to the precision of the manipulation required in these tasks, whereas in the left hand highest velocities are observed in the same groups except of G3, as in unscrewing/screwing tasks of G3 the non-dominant hand is holding the bottle/jar.

Thumb motion

Median postures of thumb joints (Figure 4.2.1) present similar median values in both hands for all the task groups, remaining flexions of thumb IP and MCP almost neutral and thumb CMC slightly flexed. Thumb median abduction is also quite constant across task groups and presents low variability. The only observed difference in right hand is the slightly extended median posture in G3 (opening and closing packages: unscrewing and screwing) and G6 (drinking), as grasps performed in both task groups require lateral pinch grasps (in the case of G3) (Figure 4.2.11, left) and cylindrical grasps of large diameter objects (in the case of G6) (Figure 4.2.11, right), leading to extended thumb postures. This observed extension of left thumb MCP in G3 (opening and closing packages: unscrewing and screwing) is far more noticeable in left hand. This is attributable to the role of the non-dominant hand in these tasks (holding the bottle/carton/jar while its cap is being unscrewed/screwed by the dominant hand), commonly performing cylindrical or lumbrical grasps that lead to a more extended thumb MCP posture. Moreover, when observing 5th percentile angles, we can observe higher extension of right thumb IP, MCP and CMC in G2 (transportation: open space), G3 (opening and closing packages: unscrewing and screwing), G4 (opening and closing packages: other), G10 (cleaning) and G13 (other), presenting especially high variability in IP and MCP, achieving values of IP extension around 75º and CMC of 50º, approximately, but both remaining within the measured AROMs. When observing 95th percentile postures, G3 (opening and closing packages: unscrewing and screwing) also presents the highest right IP flexion values, thus being the task group requiring highest thumb functional range of motion. Nevertheless, some extension outliers presenting values above 100º can be observed in G1 (transportation from open space) in carrying a baking tray, G2 (transportation from closed space) in carrying and putting into the fridge a carton of eggs and a lemon and G4 (opening and closing packages: tearing, pulling, etc.) in opening the jar of flour, which are quite out of the measured AROMs.

Figure 4.2.11: Lateral pinch grasp performed when unscrewing a cap (left) and cylindrical grasp performed when drinking (right), both requiring thumb joints extension.

When observing velocities, it can be observed that median and peak positive and negative velocities in right hand (Figure 4.2.3) are again higher in groups G3 (opening and closing packages: unscrewing and screwing), G4 (opening and closing packages: other) and G10 (cleaning), while almost null in G6 (drinking), owing to the static grasp performed in these tasks. Nevertheless, left thumb velocities are generally lower, being almost null in G5 (eating), G6 (drinking) and G12 (displacement without manipulation).

Palmar arch

Palmar arch median postures are also quite similar across task groups, observing mean postures around 10º more flexed in right hand than in left hand (Figure 4.2.1) and presenting higher variability, as left hand is less involved in precision manipulation, which requires higher palmar arch flexion than power grasps. Median values of 95th percentile flexion are around 35º, none of them being above 50º, and some extension outliers (no higher than 20º) are observed in 5th percentile posture in G4 (opening and closing packages: other), being all these values within the measured AROMs.

Palmar arch median positive and negative velocities (Figure 4.2.4 and Figure 4.2.5) are low in both hands, especially in left hand, being almost null in both hands in tasks from G6 (drinking). The only two groups where right palmar arch peak positive and negative velocities (Figure 4.2.6 and Figure 4.2.7, respectively) are over 50deg/s are G3 (opening and closing packages: unscrewing and screwing) and G10 (cleaning), while in left palmar arch are all lower, finding the highest peak velocities in G10 (cleaning).

Wrist

Both wrists tend to be extended when performing all the task groups (Figure 4.2.1), being consistent with results obtained in other studies from the research group analyzing wrist AROMs and FROMs during a set of bimanual ADLs [225]. Nevertheless, FROMs obtained for dominant and non-dominant hand in the mentioned work were almost identical, while here the right wrist is quite more extended than the left wrist. It may be attributable to the fact that most tasks in [225] were selected to have a significant implication of the non-dominant hand, while the ones from the KINE-ADL BE-UJI dataset were only selected to be representative of feeding and cooking ADLs, without considering the level of involvement of the non-dominant hand, which was sometimes in a resting position. Wrist deviations also remain quite constant and present low variability, observing in both wrists some ulnar deviation, also slightly higher in right hand than in left hand. When analysing extreme postures (P5) it can be observed that all the extension values are above 50º.

The highest wrist flexion and deviation median velocities are found in G10 (cleaning), both in right and left hands (Figure 4.2.4 and Figure 4.2.5), while the lowest values are obtained in G6 (drinking), as the movement of transportation of the recipient is performed by the shoulder and elbow and the wrist remains quite static along all the task. These same outcomes are obtained when observing peak velocities (Figure 4.2.6 and Figure 4.2.7).

Manipulability requirements of tasks

The global manipulability index (Figure 4.2.9) has been presented in a box and whiskers plot for right hand, left hand and both hands simultaneously, providing information at a glance on the role of each hand in bimanual tasks. As explained, this global index considered within hand manipulation when at least one hand joint velocity was above 10deg/s (or one in each hand when considering both hands altogether). At first sight, it can be observed that the median value of the global manipulability index was higher for the right hand in almost all the task groups, except in G2 (transportation from closed space) and G12 (displacement without manipulation). In case of transportation from closed space, this is due to the fact that subjects mainly used the left hand to open the cabinet/drawer/freezer, while the right hand held the object with a static grasp. Moreover, it can be observed that task groups with highest manipulability in both hands (separately) were G4 (opening and closing packages: pulling, tearing, etc.) and G10 (cleaning). Contrarily, tasks presenting lower levels of manipulability were, as expected, G5 (eating) and G6 (drinking), but presenting far lower manipulability for the right hand in G6. This global manipulability index is providing general information regarding required manipulability to perform the tasks, considering all hand joints together, and allowing the comparison between hands in an easily interpretable way.

Global manipulability index considering both hand motion (altogether) presents highest values in G4 (opening and closing packages: pulling, tearing, etc.) and G10 (cleaning), as these tasks imply high levels of bimanual manipulation. Contrarily, tasks requiring lower bimanual manipulation (all median values under 50%) were G5 (eating), G6 (drinking), G7 (pouring) and G12 (displacement without manipulation). These low values are coherent owing to the nature of the tasks in these groups, as in G5 (eating) and G6 (drinking) the left hand might be resting while the right hand is performing a static grasp, in G7 (pouring) both hands are performing static grasps and in G12 (displacement without manipulation) both are relaxed.

The manipulation requirements of each group of tasks have been outlined from the observation of the global manipulability index, having identified the role of each hand and which tasks require bimanual manipulation. A deeper analysis of which DoF are used for the manipulation can be performed by observing the individual manipulability index for each hand, joint and task group (Figure 4.2.8). Two groups of tasks with different within-hand manipulability requirements can be clearly identified from the plots of the manipulability index of the joints of the right hand: (i) those requiring low to medium manipulability in almost all the joints (most task groups) and (ii) those that require high manipulability, such as G3 (opening and closing packages: unscrewing and screwing), G4 (opening and closing packages: other) and G10 (cleaning), which presents median values of manipulability index above 50% in most of the DoFs (except middle-ring and ring-little abductions). From these task groups, G10 (cleaning) is the one requiring higher manipulability, presenting median values above 60% in PIPs, 65% in MCPs, 70% in thumb flexion, 60% in thumb IP flexion, 60% in palmar arch and 65% in wrist flexion and deviation, while G6 (drinking) is the one requiring generally lowest manipulability (as G12 (displacement without manipulation) also presents low values), presenting median values under 30% in PIPs and MCPs, 20% in finger abductions, 30% in thumb flexion, 30% in thumb IP flexion, 20% in thumb MCP flexion, 30% in palmar arch, 30% in wrist flexion and 25% in wrist deviation. Furthermore, it is worth mentioning that the right hand DoF presenting highest manipulability index was thumb flexion, presenting median values over 70% (as mentioned, in G10 (cleaning)), while the one presenting lowest median values was thumb abduction, which was under 10% in tasks from G12 (displacement without manipulation).

Median values of manipulability index of the left hand joints are approximately 10% lower than the right hand ones. Again, tasks can be classified into low/medium and high manipulability requirements. Once more, G10 (cleaning) is the task group requiring highest manipulability, with median values of manipulability index above 50% in PIPs and MCPs, 60% in thumb flexion, 50% in thumb IP flexion, 50% in palmar arch, 50% in wrist flexion and 30% in wrist deviation, while G5 (eating) is the one requiring less manipulability, presenting median values under 10% approximately in PIPs and MCPs, 5% in finger abductions, 20% in thumb flexion, 5% in thumb IP flexion, 10% in thumb MCP flexion, 10% in palmar arch and 10% in wrist flexion and deviation. Left hand DoF presenting highest manipulability index values was thumb flexion, with median values above 60% in G10 (cleaning), while ring-little abduction presented the lowest, being under 5% in tasks from G5 (eating).

All the outcomes from this manipulability index analysis are consistent with the ones obtained from the analysis of median and extreme velocities, being the tasks requiring highest manipulability the ones that presented highest velocity values: G3 (opening and closing packages: unscrewing and screwing), G4 (opening and closing packages: other) and G10 (cleaning); and the ones requiring lowest manipulability are the ones that presented lowest velocity values: G5 (eating) and G6 (drinking). It can be observed that task groups requiring highest levels of manipulability are composed of tasks that require high levels of within hand manipulation, precision grasps and sometimes manipulation of several objects simultaneously using both hands. Furthermore, it has been shown that thumb motion is key to meet the manipulative requirements of these tasks, at its flexion is the DoF that presented highest manipulability index, even in the non-dominant hand.

Global analysis of kinematics requirements by type of task

The observations made over the postural and velocity related parameters are summarised in Table 4.2.2, which presents all the observed extreme postures or velocities that should be considered when prescribing and designing ADs.

From the postural results it can be extracted that the degrees of freedom with more variation of values across task groups and, consequently, higher FROMs, are PIP and MCP flexions, which also present higher AROMs. These results are coherent with previous studies analysing AROMs and FROMs during the performance of a set of ADL from different fields [18], [138]. Furthermore, it has been observed that task groups such as using cutlery or unscrewing caps lead to extreme PIP and MCP flexion postures owing to the small diameter of the product or the force type required. These force types may be difficult to achieve by people with reduced hand mobility. In the same way, it has been observed that task groups with a variety of product shapes, force types and intended motion (such as cleaning) also present extreme PIP and MCP flexion postures. Contrarily, it has been observed that other tasks lead to extremely extended MCP postures, such as transportation (G1 and G2), opening and closing packages (G4) or using appliances (G9), which may be attributable to passive extensions during power grasps while holding or manipulating large objects (box of biscuits, jar of flour, etc.), during the action of pulling (to open a drawer, a fridge or an oven) or while pressing buttons (coffee machine or hob). Apart from this, other task groups presented median thumb extension higher, such as G2 (transportation: closed space), G3 (opening and closing packages: unscrewing and screwing), G4 (opening and closing packages: other), G6 (drinking) and G10 (cleaning). These thumb extensions may be attributable again to the intermediate grasp performed during the action of pulling to open drawers, cabinets, etc., to the lateral pinch grasps exerting force (as when unscrewing caps or tearing to open packages), or to the manipulation of large objects (as bowls or dishes while cleaning).

From this, we can extract that the tasks using small diameter objects may lead to extreme PIP and MCP flexion postures, while those that imply transportation and manipulation of large objects, pulling to open doors (drawer, fridge or oven) may lead to undesirable extensions of MCP and thumb joints. For this reason, especially in areas such as using cutlery, opening and closing packages (tearing and pulling, unscrewing and screwing) and drinking, using ADs when hand mobility is affected would be recommended.

From velocity-related parameters, MCP and PIP are the joints with the highest recorded angular velocities. Furthermore, there is no relationship between velocities and the intended motion of the tasks, as high peak velocities were observed both in bounded tasks (G3 (opening and closing packages: unscrewing and screwing)) and in free or half bounded tasks (G4 (opening and closing packages: other) and G10 (cleaning)). Nevertheless, we can observe that these groups that require performing a reduced set of force types including hold, lift, lift- and place (drinking, pouring or displacement without manipulation) present lower velocities.

Table 4.2.2: Main outcomes from the kinematic parameter analyses by task group. 5th and 95th percentile abbreviated as "P5" and "P95", respectively.

TASK GROUP	MEDIAN POSTURE	P5 POSTURE	P95 POSTURE	MEDIAN VEL	P95 VEL	MANIPULABLILITY INDEX
G1: Transportation: open space		▲ R MCP ext. outliers ▲ L PIP MCP ext. outliers				
G2: Transportation: closed space		▲ R L MCP ext. outliers ▲ R thumb joints ext.				
G3: Opening and closing packages: unscrewing and screwing	▲ R L thumb ext.	▲ R thumb joints ext.	▲ R PIP MCP flex. ▲ R thumb IP flex.	▲ R PIP MCP ▲ R fingers abd.	▲ R PIP MCP ▲ R fingers abd. ▲ R palmar arch over 50deg/s	▲ Index in all R joints (except middle-ring and ring-little abduction) above 50%.
G4: Opening and closing packages: tearing, pulling, etc.		▲ R L MCP ext. outliers ▲ R thumb joints ext. ▲ R palmar arch ext. outliers		▲ R L PIP MCP ▲ R L fingers abd.	▲ R L fingers abd.	▲ Index in all R hand joints (except middle-ring and ring-little abduction) above 50%. ▲ Global index in R and L hand ▲ Global index when considering both hands (≈95%)
G5: Eating						
G6: Drinking	▲ R thumb ext.					
G7: Pouring	▲ L MCP flex.					
G8: Using cutlery and kitchen utensils	▲ R PIP MCP flex. (except index) ▲ L PIP MCP flex. ▲ R ring-little finger abd. <0		▲ R PIP MCP flex.			
G9: Using appliances		▲ R MCP ext. outliers				
G10: Cleaning	▲ L MCP flex.	▲ R thumb joints ext.	▲ R L PIP MCP flex.	▲ R L PIP MCP ▲ R L fingers abd. ▲ R L wrist flex. ▲ R L wrist dev.	▲ R L PIP MCP ▲ R L fingers abd. ▲ R palmar arch over 50 deg/s ▲ L palmar arch ▲ R L wrist flex. ▲ R L wrist dev.	▲ R PIP above 60% ▲ L PIP above 50% ▲ R MCP above 65% ▲ L MCP above 50% ▲ R thumb flex above 70% ▲ L thumb flex above 60% ▲ R thumb IP flex above 60% ▲ L thumb IP flex above 50% ▲ R palmar arch above 60% ▲ L palmar arch above 50% ▲ R wrist flex. above 65% ▲ L wrist flex. above 50% ▲ R wrist abd. above 65% ▲ Global index in R and L hand ▲ Global index when considering both hands (≈95%)
G11: Opening and closing cabinets, drawers and moving chairs		▲ R PIP ext. outliers				
G12: Displacement without manipulation						
G13: Other		▲ R thumb joints ext.	▲ R PIP MCP flex.			

4.2.5 Conclusion

The aim of this work was to characterise hand kinematics during the performance of several task groups using postural and velocity-related parameters, as well as to identify patterns depending on the task characteristics or detect tasks requiring hand kinematic performance hardly achievable by people with affected hand functionality.

Considering all the outcomes from the postural analyses and the velocity-related analyses, we can conclude that some tasks require extreme postures hardly achievable by persons with hand mobility-related pathologies, being especially affected PIP, MCP and thumb joints. Among these task groups we mainly identified opening and closing packages (unscrewing and screwing, pulling, tearing, etc.), using cutlery and kitchen utensils and cleaning tasks. Furthermore, opening and closing packages (unscrewing and screwing, pulling, tearing, etc.) and cleaning presented higher joint velocities, also hardly achievable by some users. These velocities were closely related with the dexterity required to perform the task, rather than other parameters such as intended motion. Nevertheless, it was observed that parameters such as force type affected joint velocity, as those tasks requiring static forces (e.g. hold, lift, lift- and place) presented lower velocities.

This work also proposed the use of the manipulability index, which was found to be an easily interpretable indicator of velocity profiles during task performance and the required manipulability to perform the task. Additionally, global manipulability index was calculated for right hand, left hand and both hands altogether, providing interesting information on the role of each hand in bimanual tasks.

Apart from these mentioned outcomes, which may help to correlate task characteristics to kinematic parameters, this work evidences the need of using ADs when performing cooking and feeding tasks such as unscrewing caps, opening packages, carrying and manipulating large objects and using cutlery or kitchen utensils when user's hand mobility is reduced. In the same way, it is recommended looking for alternatives when cleaning and washing the dishes is required.

As mentioned, the novelties that presents this work are the wide variety of representative feeding and cooking bimanual tasks considered, the fact of analysing both hands joints, and the study of both postural and velocity-related parameters, allowing a more holistic interpretation of hand kinematic behaviour. Nevertheless, this work may present some limitations, such as the effect on manipulation dexterity of wearing an instrumented glove, and therefore, on joint velocity. Nevertheless, the tasks studied were selected from the KINE-ADL BE-UJI Dataset, which was tailored so as to only include tasks requiring medium and low manual dexterity, therefore being minimally affected by the use of instrumented gloves. Another limitation is the variety of fields of tasks considered, which is limited (only cooking and feeding). Nevertheless, the intention is to broaden this study as the KINE-ADL BE-

UJI Dataset is enriched with additional tasks from other fields key for personal autonomy.

Chapter 5

Effect of assistive devices on hand kinematics during activities of daily living

5.1 Introduction

Ageing and different pathologies affect mobility and strength, reducing capabilities to perform activities of daily living (ADLs) [221], thus reducing personal independence. The reported effects of those physical conditions on the human hand are varied, such as joint rigidity or decreased hand aperture in patients with Parkinson's disease [226] or decreased grasp stability, independent finger control and force control in cerebral palsy patients [148]. Furthermore, some patients with specific hand and wrist pathologies such as carpal tunnel syndrome also present pain while performing ADLs [227]. This loss of ability to perform ADLs has been related in the literature with a decrease of quality of life [228], depression [229] and increase of risk of mortality [230]–[232], among other things.

In order to overcome these difficulties, there are different commercially available assistive devices (ADs), whose primary purpose is to maintain or improve an individual's functioning and independence to facilitate participation and to enhance overall well-being [233].

When the use of an AD is recommended, therapists are responsible for selecting the most appropriate AD for each patient, choosing among different ADs designed to perform the same task. Nevertheless, this selection is not an easy process, since there are no tools available to measure the effects on objective biomechanical parameters of using ADs. Hand posture, as well as upper limb posture, grip strength or hand joint kinematics can be affected by their use. Thus, therapists must make decisions based on their own clinical experience, what leads to a call to cater for training needs regarding ADs assessment [234].

According to Kraskowsky et al. 2001 [235], inappropriate prescription and distribution of ADs wastes time that could be better spent on adaptations that a patient would find more suitable to his/her needs. Furthermore, it implies a spend of private and public funds by supplying adaptive equipment that may never be used. Apart from this, patients' perceptions regarding the AD prescribed takes an important role on the process. Prescribing an AD that is perceived by the patient as not needed will lead to patient's rejection of the product [236]. Therefore, this first selection phase is decisive for the success of the therapy, and quantifiable data regarding the effects of using each type of AD would be key to ensure the right choice.

Some works in literature studied qualitative parameters while using ADs, as reasons of rejection [235] or problems arising from their use [237], while other studies went further and quantified the effects of using different feeding ADs [144], [146]–[148]. These quantitative analyses only focused on cutlery ADs, but some conclusions regarding the effect of product shape were drawn. These results gave a glimpse of the relationship between ADs shape and upper limb kinematics, which can be used to quantify ADs effect and, therefore, contribute to a better ADs prescription.

This chapter deals with the quantification of the effects while using ADs during the different activities of daily living required for personal autonomy. The assessed products are upper limb mobility ADs to perform feeding, cooking and self-care ADLs. They have been assessed in two different sub-studies, and different conclusions regarding their effect on hand and upper limb kinematics are drawn.

The first part of the study consisted of a comparative analysis of the entire upper limb posture, in global terms, while performing a set of tasks using normal products and ADs. For such global analysis, postural data were collected using a visual analysis method, rather than a motion capture system. The posture analysis comprised all main segments of the entire upper limb (shoulder, elbow, wrist and hand), as upper limb joints posture depends on the features of product or AD manipulated. Therefore, grasp types and postures of both shoulders, elbows and wrists were analyzed, as well as contact ratio of fingers and palms and time of accomplishment of the tasks.

After observing the global effects on the entire upper limb, the second part of the study went deeper on the effects of the same set of AD on the hand kinematics. This experiment consisted in a comparative study of hand joint kinematics, recorded with the CyberGlove while performing ADLs using normal products and ADs. Mean postures, ROMs, median velocities and peak velocities were compared and related to the design feature that each AD had regarding their correlative normal product. An overview of the observed effects in the different parameters and the AD design is given, as well as examples of pathologies that patients would benefit of using each AD design typology.

Note that all the ADs and tasks analysed were the same in both parts of the study, except in two specific cases: buttoning and unbuttoning a shirt and eating with an AD spoon/fork adapter made of a nylon strap. The buttoning and unbuttoning task was excluded from the second part of the study owing to the manipulation precision required to perform it, which was reduced when wearing the instrumented glove, as previously observed in section 3.2. The spoon/fork adapter was excluded because no grasp was required during its use, as this product consisted in a strap attached to the hand.

5.2 Effect of assistive devices on hand and arm posture

The work presented in this section was published in Applied Ergonomics under the title "Effect of assistive devices on hand and arm posture during activities of daily living" [238].

5.2.1 Introduction

Ageing and different pathologies reduce hand mobility and grip strength, hindering the normal performance of activities of daily living (ADLs) [221], therefore affecting personal independence. There are different commercial adaptive products or assistive devices (ADs) aimed at making it easier to carry out some ADLs in these situations by overcoming the difficulty of grasping and manipulation arising from the use of standard products. Therapists are responsible for indicating the most suitable product for each patient, and have to choose from among different available ADs designed to carry out the same task. However, this selection is not an easy decision, since there are no tools to evaluate the potential impact of each product on the improvement of patients' quality of life or any information about the side effects resulting from its use. Therefore, therapists must make decisions based on their own clinical experience, which leads to a call to cater for training needs regarding appropriate product assessment [234]. A detailed objective study about the effect of their use could be essential to determine recommendations and precautions when using ADs.

Some studies have presented reviews of ADs available on the market for different fields, such as feeding [239], personal care [240], [241] or mobility [242], but they only offer qualitative descriptions of the products and the difficulties presumably overcome. The use of ADs during the performance of ADLs has been studied mainly from data collected through user surveys or group discussions [235]–[237], [243]–[246]. These studies were focused mainly on identifying the reasons for rejection. Rejection was found to depend on factors such as equipment suitability (pre-prescription home visits), perception of the product, anxiety, adequate training or the conviction that the AD was not needed [235], [236], [244], [245]. Furthermore, the problems arising from using ADs were found to be related to the type of impairment [237] and the number of ADs used was seen to depend on the severity of the impairment. In children with disabilities, the studies have also dealt with the use of ADs in schools or education [243], stressing the need for both verbal information and practical experience. Despite all these useful conclusions, however, the results remain qualitative.

Only a few studies have attempted to quantify the effect of the use of ADs on the hand and upper limb posture [144], [146]–[148]. Some of these experimental studies were carried out on healthy subjects performing some ADLs [144], and others on subjects with pathologies such as Parkinson's [146], [147] or cerebral palsy [148]. Although these studies have analysed the effect on hand posture [144], arm posture [146], [148] and hand-arm posture [147], the ADL considered was only the task of eating with a spoon [144], [146]–[148]. Important conclusions were drawn from these works, such as the importance of the effect of the diameter of the handle of the product on the speed and smoothness of the hand movement [147]. Kinematics was also found to affect the perceived comfort, the products handled with greater speed and smoothness being rated better [147]. However, the hand kinematics analysis was very limited, only taking into consideration the range of motion of interphalangeal and metacarpophalangeal joints [144] or the number of fingers involved in the grasp [147].

Registration of all hand joint angles simultaneously without affecting the normal use of products is challenging. To get round this, many studies in the field of ergonomics and safety at work are based on direct observation of the posture [247]. In this line, several methods are widely used, such as the Ovako Working Posture Analysis System (OWAS) to evaluate the overall body posture [169] or the Rapid Upper Limb Assessment (RULA) to assess the upper limb postures [24]. Some recent studies that have used video recording and posture classification to describe the posture of hands [2], [25], [129] have employed grasp taxonomies to classify hand posture in more detail and may complement posture classification methods.

The aim of this work is to analyse the effect of ADs on hand and arm postures, on the basis of the relationship reported in the literature between kinematics and comfort. To do so, the postures employed by healthy subjects when using ADs during the performance of a variety of ADLs are compared to those utilised when performing the same ADL with standard products. Due to the wide variety of ADs available in the aspect of mobility, self-care and domestic life, and the importance of these fields for personal independence, it was considered appropriate to compare the hand and arm postures during the performance of representative ADLs from these fields. This comparison may help to understand ADs users' rejection and contribute to a better assessment of ADs depending on the pathologies or impairments that their use is intended to supplement. In addition, the study of these postural effects may be useful during the design of new products focused on specific pathologies.

5.2.2 Material and methods

Ten healthy right-handed subjects (5 male, 5 female; age 35.1 ± 13.8 years) volunteered to participate in the experiment, approved by the university ethics committee. The subjects were previously informed about the characteristics of the experiment and gave their written consent.

Selection of tasks and material

After studying the different types of ADs for grasping that are commercially available (such as personal care, dressing, eating or drinking), 22 products were chosen as being representative. Then, in accordance with the ADs that were chosen, 13 ADLs associated with their use were selected from the World Health Organization's International Classification of Functioning, Disability and Health (ICF). All the specific tasks selected are listed in Table 5.2.1. Each of these tasks was carried out with the normal products and with one, two, three or four ADs (Figure 5.2.1), except task 11 (brushing hair), in which half of the subjects used a normal and an adapted comb, while the other half used a normal and an adapted brush.

Table 5.2.1: ADLs performed in the experiment and products used during their performance (NP: normal product, AD: assistive device).

ID	TASK	PRODUCTS
1	Opening cans	1 NP, 1 AD
2	Unscrewing a bottle top	1 NP, 2 ADs
3	Pouring from a bottle	1 NP, 1 AD
4	Pouring from a carton	1 NP, 1 AD
5	Drinking from a glass	1 NP, 1 AD
6	Eating with a spoon	1 NP, 4 ADs
7	Eating with a fork	1 NP, 4 ADs
8	Carrying a dish	1 NP, 1 AD
9	Using a tap	1 NP, 1 AD
10	Brushing teeth	1 NP, 1 AD
11a	Brushing hair (comb)	1 NP, 1 AD
11b	Brushing hair (brush)	1 NP, 1 AD
12	Sliding a zip up/down	1 NP, 2 ADs
13	Buttoning/unbuttoning a shirt	1 NP, 2 ADs

Figure 5.2.1: Products used during the performance of the ADLs considered in the experiment.

Three scenarios were prepared (Figure 5.2.2). The objects were arranged in the same position for all the subjects, and the initial and final postures of each subject were controlled to ensure they were the same.

Figure 5.2.2: Scenarios prepared for the experiment. (Scenario 1: A chair with the objects to perform the dressing tasks. Scenario 2: A table with the objects to perform the eating/drinking tasks. Scenario 3: A sink and a table with the objects to perform the self-care tasks).

Experiment

Before actually carrying out the tasks, subjects were given instructions on the use of the products and on how to perform the tasks. The subjects were recorded on video while performing the selected ADLs with the normal products and the ADs. The subjects performed the tasks with the hand they preferred, and with both hands when needed. Several of them, even being right-handed, performed some tasks with their left hand (using the tap, for example). Furthermore, because of the way the buttons were set out on the shirt, the AD was held with the left hand in the task of buttoning and unbuttoning a shirt. The order of the tasks and scenarios to be performed by each subject was randomised, and subjects were not given any extra time to get used to the ADs.

Data analysis

The video recordings were analysed in order to separate the tasks into elementary grasp actions (EGAs), defined as those in which the hand maintained a specific type of grasp. For each EGA, the type of grasp for both hands, the parts of both hands in contact with the object, the posture of both arms and the duration of the EGA in seconds were identified by visual analyses. These analyses were performed by a single trained observer throughout all the experiments in order to avoid bias. The postures of the shoulder, elbow and wrist were identified qualitatively following a classification based on that proposed in the RULA method [24]. Shoulder flexion/extension (F/E) was classified as neutral, slightly flexed or highly flexed, and shoulder abduction/adduction (AB/AD) as neutral, abducted or adducted. Regarding the elbow postures, F/E was classified as neutral, flexed or extended, and pronation/supination (P/S) as neutral, pronated or supinated. Finally, wrist F/E was classified as neutral, flexed or extended, and wrist AB/AD as neutral, abducted or adducted. For arm postures on the borderline, the closest-to-neutral zone was always considered, as the most favourable case. The hand posture analysis was performed using a seven-grasp type taxonomy (Figure 5.2.3), previously used by the authors to study the frequency of use of grasps during ADLs [2]. This taxonomy also classifies those grasp types into power or precision grasps, as specified in Figure 5.2.3. Regarding the analysis of the hand parts in contact with the object during the grasp, six hand zones (the palm, the thumb and each of the four fingers) were taken into consideration. In the cases in which the identification of the arm posture or contacts was not possible by observation, these data were considered as missing or not available (NA).

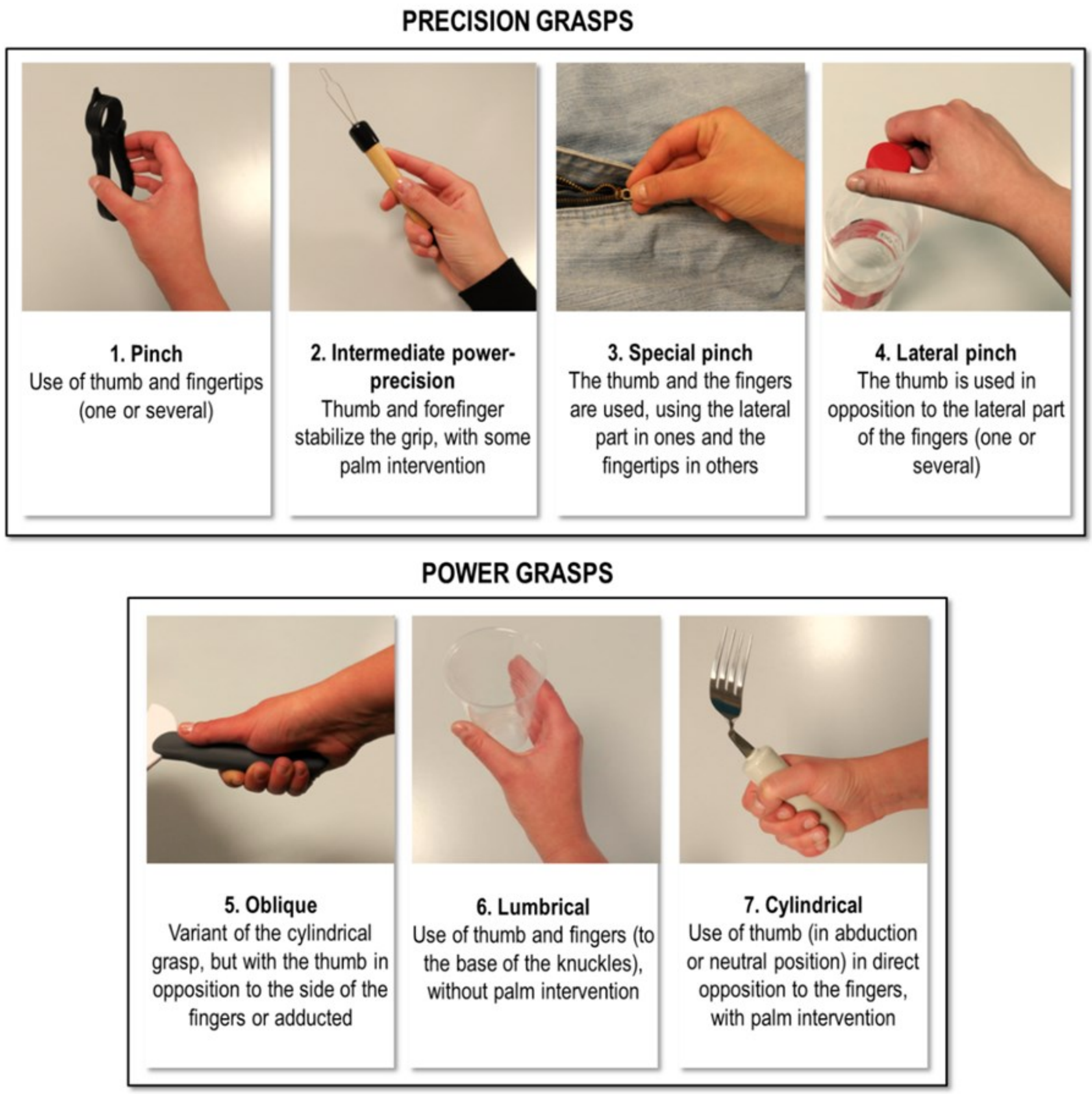


Figure 5.2.3: Grasp classification.

Firstly, in order to have an overview of the recorded data, the time required to accomplish each task (per subject and product) and the overall time spent using each hand for each task and product were computed (in seconds). Then, to check for statistical differences in the time required to accomplish the tasks with normal products and with ADs, a repeated measures ANOVA was performed, using the type of product (normal and the different ADs for each task) as the within-subjects factor. The descriptive analysis of these data showed that the time of accomplishment of the tasks was quite different between subjects and tasks. Therefore, in order to ensure that all the tasks, products and subjects were weighted to the same extent in all the subsequent analyses, the original durations of the EGAs (in seconds) were normalised with the duration of their corresponding record. In this way, each record (each task performed by each subject with each product) had a duration of 100 equivalent seconds. The percentages of time spent using the different types of grasp per hand, contacts of the hand with the objects and arm postures were obtained from the equivalent durations, and descriptive statistics were used to identify differences between the use of ADs and normal products. Different contingency tables for percentages of time of use were computed and the associated chi-square test was applied to identify whether the differences observed between standard products and ADs were statistically significant. The contingency tables of percentage of time were: type of grasps × product (two 7×2 tables, one per hand); hand contact zones × product (twelve 2×2 tables, six per hand) and neutral postures of the wrist, elbow and shoulder × product (six 2×2 tables, one per hand and arm joint). In the case of each 7×2 table for type of grasps, the post-hoc analysis was performed by computing seven new 2×2 tables, one per grasp and applying the Bonferroni correction to the bilateral asymptotic significance level in order to compensate for the number of grasp types analysed at the same time. After that, chi-square tests were also computed in the same way for grasp types and arm postures but separating for each AD in comparison with its corresponding standard product.

5.2.3 Results

The total amount of time spent using the right and left hands during the experiments was 46 min 51 s and 23 min 35 s, respectively. The amount of time that only the right hand (without using the left) was used was 23 min 57 s, while the left hand alone was used for only 42 s, mainly for reaching objects or in the zipping tasks. Table 5.2.2 details the amount of time used by each hand to perform each task.

*Table 5.2.2: Total amount of time that each hand (R: right hand, L: left hand) was used to perform the different tasks during all the experiment when performed by all the subjects with normal products (NP) and ADs. *Note that the time for these tasks corresponds to all of the ADs jointly.*

	TIME (s)			
	NP		ADs*	
TASK	R	L	R	L
Opening cans	38	38	106	97
Unscrewing a bottle top	33	33	152 *	135 *
Pouring from a bottle	39	22	42	19
Pouring from a carton	43	12	45	11
Drinking from a glass	49	-	48	23
Eating with a spoon	67	-	308 *	-
Eating with a fork	67	-	315 *	-
Carrying a dish	59	59	92	14
Using a tap	28	14	45	6
Brushing teeth	91	-	86	-
Brushing hair (comb)	38	2	35	1
Brushing hair (brush)	25	-	29	-
Sliding a zip up/down	35	38	107 *	102 *
Buttoning/unbuttoning a shirt	100	100	689 *	689 *
TOTAL	712	318	2099	1097

Figure 5.2.4 shows the box-and-whiskers plot of the time required to accomplish each task when performed with normal products and with ADs. Significant differences (bilateral asymptotic sig. ≤ 0.05) were found after an

ANOVA for the tasks of opening cans (1), unscrewing a bottle top (2), eating with a spoon (6) (only for the adapted spoon A2), carrying a dish (8), sliding a zip up and down (12) (only for the adapter A1) and buttoning/unbuttoning a shirt (13). It can be observed that the time of accomplishment in all of these tasks with differences was far higher when performed with ADs. This can be attributable to the lack of experience of the subjects with ADs, owing to the fact that all of them were healthy.

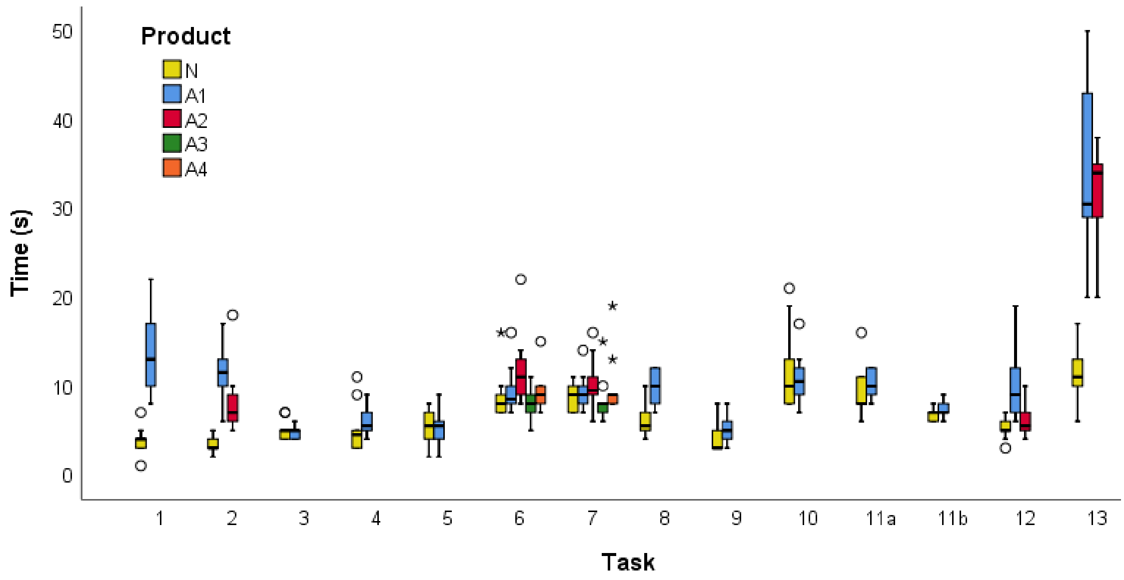


Figure 5.2.4: Time of accomplishment of the tasks.

Table 5.2.3 shows the percentages of time of use of each type of grasp separated for normal products and ADs (obtained from equivalent durations). Significant differences were found after the chi-square test, with a bilateral asymptotic sig. ≤ 0.0071 (after applying the Bonferroni correction) for all the grasp types, except for the special pinch one with the right hand, where the differences obtained were far lower than for the rest. It can be observed that the time of performance of precision grasps (pinch and lateral pinch) decreased when using the ADs, while an increase was found for power grasps such as cylindrical or oblique.

Table 5.2.4 shows the statistically significant differences found in the time of use of each grasp type per hand in each task and AD used after applying the Bonferroni correction. It can be observed that significant differences were found for almost every grasp type and object, and also that there was an increase in oblique and cylindrical grasps while using ADs and a decrease in the lateral and pinch ones.

Table 5.2.3: Percentage of equivalent time of use of each type of grasp for each hand when using normal products (N) and assistive devices (ADs). Significant differences are underlined.

		Right hand (%)		Left hand (%)	
		N	ADs	N	ADs
Power grasps	Cylindrical	20.7	25.5	33.5	44.5
	Lumbrical	6.4	3.5	13.2	7.1
	Oblique	10.5	36.6	2.8	6.2
Precision grasps	Special pinch	10.8	10.3	13.8	4.4
	Intermediate	10.6	5.7	5.0	18.0
	Lateral	18.0	3.6	6.6	2.1
	Pinch	22.0	9.9	22.0	14.1

Table 5.2.4: Statistically significant differences in time of use of each grasp type and task while using normal products (NP) and ADs for both right (R) and left (L) hands. Sign criteria: (+) for higher values while using ADs; (-) for lower values while using ADs; (=) when no differences were found. Empty cells for the left hand when only the right hand was used.

	CYL		SPE		INT		LAT		LUM		OBL		PIN	
TASK	R	L	R	L	R	L	R	L	R	L	R	L	R	L
Opening cans	+	=	=	=	+	+	=	=	+	=	+	=	-	-
Unscrewing a bottle top (A1)	+	+	-	=	=	=	-	-	+	=	+	=	=	=
Unscrewing a bottle top (A2)	=	=	+	=	=	=	-	=	+	+	=	=	+	=
Pouring from a bottle	-	+	=	=	=	=	=	=	=	=	+	=	=	=
Pouring from a carton	-	=	=	=	=	=	=	=	-	=	+	=	=	=
Drinking from a glass	=	=	=	=	=	=	=	=	-	=	+	=	=	=
Eating with a spoon (A1)	+		=		=		-		=		+		=	
Eating with a spoon (A2)	+		=		=		-		+		+		=	
Eating with a spoon (A3)	+		-		-		-		=		=		-	
Eating with a spoon (A4)	+		=		+		-		+		+		=	
Eating with a fork (A1)	+		-		-		-		+		+		=	
Eating with a fork (A2)	+		-		=		-		=		=		=	
Eating with a fork (A3)	+		-		-		-		=		-		-	
Eating with a fork (A4)	+		=		-		-		=		+		=	
Carrying a dish	+	=	-	=	-	-	=	=	-	-	+	=	-	+
Using a tap	+	+	=	=	-	-	-	-	=	=	+	=	=	=
Brushing teeth	+		=		-		=		=		+		=	
Brushing hair (comb)	=	=	-	=	=	=	=	=	=	=	-	=	+	=
Brushing hair (brush)	+		=		-		=		=		+		=	
Sliding a zip up/down (A1)	=	=	+	=	=	+	-	-	+	=	+	=	-	=
Sliding a zip up/down (A2)	=	=	-	=	+	=	-	-	=	=	=	=	-	+
Buttoning/unbuttoning a shirt (A1)	=	+	+	-	=	+	=	=	=	=	=	+	-	-
Buttoning/ unbuttoning a shirt (A2)	=	+	+	-	=	+	=	=	=	=	=	=	-	-

Table 5.2.5 shows the contact rates (obtained from the equivalent durations) for each hand while using normal products and ADs. Significant differences (bilateral asymptotic sig. ≤ 0.05, underlined values) were found for all the parts except for the left index finger. An increase in the contact of the palms, the middle fingers, ring fingers and little fingers can be observed while using ADs, as well as a decrease in the contact of the thumbs and the right index finger.

Table 5.2.5: Palm and fingers contact rates (CR) with normal products (NP) and ADs for both hands. Significant differences are underlined.

Contacting part	Right hand		Left hand	
	NP CR (%)	ADs CR (%)	NP CR (%)	ADs CR (%)
Palm	42.6	68.6	42.7	71.8
Thumb	99.7	96.7	98.3	96.6
Index finger	98.8	97.0	98.3	98.1
Middle finger	85.2	93.4	88.5	93.2
Ring finger	57.4	80.2	70.0	86.1
Little finger	46.9	71.3	56.3	83.8

Table 5.2.6 shows the rates of neutrality of the postures of shoulders, elbows and wrists (and all possible combinations of these joints) while using the normal products and ADs (obtained from the equivalent durations). Significant differences (bilateral asymptotic sig. ≤ 0.05, underlined values) were found in the postures of all the joints and their combinations. A more detailed analysis is presented in Table 5.2.7, where the rates of neutrality of the postures using the different products for each task are compared, and the statistically significant differences are marked. It can be observed that significant differences (bilateral asymptotic sig. ≤ 0.05) were found for almost all the tasks and products.

Table 5.2.6: Shoulder, elbow and wrist rates of neutrality (NR) while using normal products (NP) and ADs. Significant differences are underlined.

Arm segment	Right arm		Left arm	
	NP NR (%)	ADs NR (%)	NP NR (%)	ADs NR (%)
Shoulder	72.5	70.6	84.8	87.6
Elbow	30.0	22.0	59.0	54.6
Wrist	77.9	74.9	87.3	81.7
Shoulder and elbow	26.0	20.2	52.7	49.0
Shoulder and wrist	59.9	57.5	75.4	71.1
Elbow and wrist	25.8	19.7	53.2	45.4
Shoulder, elbow and wrist	23.0	18.5	46.9	40.2

Table 5.2.7: Significant differences in rates of neutrality while using the normal products (NP) and ADs for each task for shoulder, elbow and wrist postures. (=) indicates that no significant differences were found and (+) indicates that postures were more neutral while using ADs. When postures were less neutral, the postures that increase are indicated in each cell, ordered from a higher to a lower rate of increase. Empty cells for the left hand when only the right hand was used. Posture abbreviations: SF (slightly flexed), F (flexed), E (extended), AB (abducted), AD (adducted), P (pronated), S (supinated).

	SHOULDER		ELBOW		WRIST	
TASK	R	L	R	L	R	L
Opening cans	SF	+	S, P, F	=	AB, E, AD	+
Unscrewing a bottle top (A1)	+	+	P	+	AB, AD	=
Unscrewing a bottle top (A2)	+	=	+	+	=	=
Pouring from a bottle	=	AB	=	=	+	=
Pouring from a carton	=	AB	=	=	E, AD	=
Drinking from a glass	SF	=	=	=	+	=
Eating with a spoon (A1)	+		P, S		=	
Eating with a spoon (A2)	+		F, P, S		=	
Eating with a spoon (A3)	=		S, P		AD, F	
Eating with a spoon (A4)	=		P, S		F, AD	
Eating with a fork (A1)	SF		P, F		=	
Eating with a fork (A2)	SF		P		=	
Eating with a fork (A3)	SF		=		AD, F, E	
Eating with a fork (A4)	SF		P		=	
Carrying a dish	SF	=	P, S, E	E	+	+
Using a tap	=	+	=	=	=	=
Brushing teeth	=		=		E	
Brushing hair (comb)	=	=	P,S,E	=	=	=
Brushing hair (brush)	=		F,S		=	
Sliding a zip up/down (A1)	=	=	=	=	AD	=
Sliding a zip up/down (A2)	=	=	=	+	=	+
Buttoning/unbuttoning a shirt (A1)	=	=	S	=	F	F, AD, AB
Buttoning/ unbuttoning a shirt (A2)	=	=	=	F	F	F, AD, AB

5.2.4 Discussion

In general terms, the results from the analysis of grasp types show that precision grasps are less frequent than power grasps when using ADs, as expected due to the presence of thicker handles. This is coherent with the results obtained from the study of the contacts of the palm and fingers. While the thumb and index fingers (commonly used in precision grasps) decreased their rate of contact while using ADs, the palm and the rest of the fingers (used in power grasps) increased it. Furthermore, the results obtained from the video analysis show less neutral postures of the arm in the tasks with fewer precision grasps and more power ones (see tasks of unscrewing the bottle top (A1), eating with spoons (A3, A4), eating with fork (A1-A4) or brushing one's hair with a brush). These results may be explained by the use of less neutral arm postures to compensate for the lack of precision of the power grasps. These results are also in accordance with Landsmeer (1962), who stated that in power grasps all the movements of the object have to be generated by the arm joints, while in precision handling the hand is able to perform the entire movement, without requiring any movement of the arm.

From the analysis of grasp types it can be observed that even though differences were obtained for almost all the products, not all these differences implied a decrease in precision grasps. The products used in the tasks of unscrewing a bottle top, eating with a spoon, using the tap, brushing teeth and brushing one's hair with a brush were the ones that presented a decrease in precision grasps and an increase in power ones. The differences in other tasks arose, however, because of the substitution of the grasp by another of the same type (power or precision), such as the task of pouring from a carton (which presented a higher rate of oblique grasps and a lower rate of cylindrical and lumbrical ones) and the task of drinking (which presented a higher rate of oblique grasps and lower rate of lumbrical ones). Nevertheless, the rest of the tasks presented differences both in power and in precision grasp types. In some cases, an increase in precision grasps was found but always accompanied by an increase in another type of power grasp. In sum, no AD increased the rate of precision grasps significantly (which is coherent with the first global analysis of grasp types, where a general increase in power grasps was obtained). Yet, results show that some products are more suitable than others for people with reduced hand mobility, as some of them still require the use of precision grasps, which may be difficult for them to perform. Precision grasps require an independent movement of the joints and a placement of the fingertips so that the object can be held correctly (which involves an opposition and rotation of the thumb) [10]. These required movements are unfeasible for many pathologies, such as osteoarthritis, where the joints that are most affected by the pathology are the distal interphalangeal joints and the base of the thumb [248], generally resulting in a reduction in both joint mobility and grip strength [249].

In a detailed study of the results from the arm posture analysis, a less neutral posture was observed in all the joints and combination of several joints when using ADs. On analysing the effect of the products used in each task, it can be seen that only the bottle opener A2, the tap AD and the zip adapter A2 produced a more neutral posture for all the arm joints. Other products produced combined effects, such as the bottle handling AD, which produced a more neutral posture for the right wrist and a less neutral posture for the left shoulder. Other products that also gave rise to combined effects were the can opener AD, the bottle opener A1, the glass adapter, the spoons (A1 and A2) and the dish adapter. Nevertheless, the tasks of pouring from a carton, eating with a spoon (A3 and A4), eating with a fork, brushing one's teeth, brushing one's hair (comb and brush), sliding a zip with A1 and buttoning and unbuttoning a shirt presented less neutral postures for some of the arm joints and, in some cases, for two joints at the same time (e.g. the A3 and A4 spoons produced less neutral postures for the right elbow and wrist). In general terms, they produced more flexed postures of the right shoulder, more extreme postures of pronation/supination of the right elbow, a more flexed posture of the left wrist and more extreme postures of abduction/adduction and flexion of the right wrist. These effects may hinder manipulation in patients in whom these joints are affected, and therefore special care should be taken when prescribing ADs in these cases. These results are in line with those from previous studies that showed that the problems arising when using some ADs depended on the type of impairment [237].

The ADs considered implement different changes in the design of the original products. Some of the ADs used in the eating tasks have thicker bent handles (A1, A2, A4), which were observed to provide less neutral postures for the shoulder and elbow in the case of the forks and for the elbow and wrist in the case of spoons. Nevertheless, the A3 adapter (when using the fork), with a thicker but not bent handle, was the only AD fork that presented less neutral postures for the wrist. Therefore, as a thicker handle requires the use of a power grasp, it generates a lack of precision that has to be offset with wider ranges of motion in the rest of the arm joints. Moreover, bending the handle seems to solve this effect at wrist level, at least when using the forks.

Some ADs that implement thicker handles or just additional ones, such as buttoning and unbuttoning ADs, have questionable effects on arm posture, since they generate less neutral postures for the wrist. The same problem appears in the task of opening a bottle with the opener A1, which required a wider range of movement of the elbow and wrist while performing the task, while the opener A2 (with no handle added) did not produce this effect. This same opener A1 was also used in the task of opening a can and, even using it in a different way, it produced the same effect on the right elbow, wrist and shoulder. In the task of carrying a dish, a similar effect on the shoulder and elbow was observed. Less neutral postures were also found during the task of pouring from a carton, drinking from a glass, brushing one's teeth, brushing one's hair (with the comb and the brush), using the A1 zip adapter and buttoning and unbuttoning a shirt. The conclusion here may be that thicker handles or extra handles added to the device in order to help carry out the task reduce the precision of the grasp, which could give rise to side effects to be studied in further work. These results highlight the importance of distinguishing between ADs compensating for a lack of grip strength and those compensating for a loss of dexterity, as considered in a previous study [250]. As pointed out in that work, ADs that compensate for loss of grip strength are most commonly used in pathologies such as rheumatoid arthritis. Nevertheless, these patients (commonly elderly adults) may also present reduced mobility in the entire upper limb, such as osteoarthritis patients [249]. According to the results of this work, care should be taken not to prescribe an AD that requires less neutral postures of the arm joints when compensating for the lack of grip strength. In these cases, the prescription may not be based on the pathology, but on the patient's specific diagnosis and reported limitations. It is important to take this aspect into account, because in pathologies such as osteoarthritis opener ADs are very common [251] and, as the results show, there may be different designs available which can thus produce different effects on the entire upper limb.

Before ending, it is important to remark on the limitations of the study. On the one hand, the number of subjects participating in the experiment was low

(5 males, 5 females), and they did not suffer from any impairment or pathology. However, they were selected so as to have different (normally distributed) hand sizes in order to obtain representative data of a healthy adult population. Furthermore, as regards the variety of activities and ADs considered, the sample size was large enough (130 for normal products and 220 for ADs) to obtain overall results for ADs. On the other hand, the visual method used to identify the arm posture may have introduced some uncertainty for postures on the borderline, but in these cases a conservative solution was adopted (closest-to-neutral zone was assumed). Furthermore, in order to avoid systematic bias, a single trained observer performed the entire analysis. In future work it would be interesting to recruit a higher number of subjects with different pathologies in order to quantify the effect of the same products depending on the impairment.

Taking into account all the results reported, it can be concluded that not all the products may be suitable for all pathologies. Some products were found to require less neutral postures, and perhaps a redesign is needed if they are intended to assist patients with pathologies affecting upper limb mobility. In this sense, a pathology-oriented design of ADs, focused on the effects of each product on certain joints, could be interesting. This pathology-oriented design would be a significant aid for therapists in the process of selecting ADs. Furthermore, it would be a way to ensure that patients' quality of life is being improved by using the AD, which is, ultimately, their main purpose.

5.3 Effect of assistive devices on hand kinematics

The work presented in this section was published in PeerJ – Life & Environment under the title "Effect on hand kinematics when using assistive devices during activities of daily living" [37].

5.3.1 Introduction

Ageing and different pathologies reduce hand mobility and grip strength, affecting the normal performance of activities of daily living (ADLs) [221] and thus limiting personal independence. To overcome these difficulties, there are different commercially available assistive devices (ADs). Since there are several types of ADs aimed at helping to perform the same ADLs, the prescription process is not an easy task, and therapists must make decisions based on their own clinical experience. Therefore, any information about the effect of the ADs is essential in order to ensure that the prescribed AD will help to overcome the user's limitations and improve his/her quality of life. Nevertheless, there is still little quantifiable information about the effect produced by the use of ADs.

Several works in the literature have presented reviews of ADs from different fields such as feeding [239], personal care [240], [241] or mobility [242], but they only offer qualitative descriptions of the products and the difficulties that are presumably overcome. The use of ADs during the performance of ADLs has been studied mainly through user surveys or group discussions [235]–[237], [243]–[245], focused on the identification of the reasons for rejection. Several useful conclusions were drawn from these works, such as the importance of the occupational therapist's involvement in selecting devices due to inadequate information about the patients [237] and also the importance of considering the user's perceptions and opinions during the AD selection process in order to prevent non-use [244]. Nevertheless, the results remain qualitative.

Little research has attempted to study the quantitative effect of using ADs on the hand and upper limb posture [144], [146]–[148]. These experimental studies were conducted on healthy subjects [144] and on subjects with pathologies such as Parkinson [146], [147] or cerebral palsy [148]. In these studies, parameters such as hand posture [144], arm posture [146], [148] or hand-arm posture [147] were analysed and some conclusions were drawn. The product handle diameter was found to affect the speed and smoothness of upper limb movement [147], evidencing a relationship between the product shape and hand kinematics. Moreover, the kinematics were also found to be affecting the perceived comfort, products that could be managed with higher speed and smoothness being better rated by the users [147]. Nevertheless, the hand kinematic analysis performed in all these studies had important limitations. One of them only considered metacarpophalangeal and interphalangeal flexion angles, which were measured manually with an electrogoniometer while performing a static grasp representative of the AD usage [144]. The other works studied the smoothness or velocity of arm movement with a three-dimensional ultrasonic measuring system using a single marker attached to the wrist of the participant's dominant hand, which only allowed the arm movement to be studied, excluding the hand [146]–[148]. In addition, the ADLs considered in the above mentioned quantitative analyses were very limited, considering only the task of eating with a spoon [144], [147], [148].

However, there is little information in the literature about the kinematics of all the hand joints during the entire task performance when using different ADs (owing to the wide variety of products available) in comparison with normal products. Kinematic parameters such as range of motion (ROM) or mean postures [252], as well as velocities and smoothness ratio [253], [254] are essential to quantify the efficiency of the task performance and are therefore useful to assess the abilities of individuals with impairments or in rehabilitation processes.

A continuous record of all joints during the entire task performance is required for a representative study of the kinematics, which allows the calculation of velocities. Nevertheless, recording all hand joint angles simultaneously without affecting the normal use of products is challenging. In this respect, instrumented gloves or videogrammetry are the techniques most commonly used for hand posture analysis when the study of a large number of joints is intended. However, data acquisition with videogrammetry during ADLs is not feasible because of the occultation and collision of markers, instrumented gloves being an alternative.

Therefore, the aim of this work is to analyze the effect of ADs on hand kinematics not only focusing on the ROM, but also on the mean postures and velocities. To do so, the hand kinematics of healthy subjects when using ADs during the performance of a variety of ADLs is compared with hand kinematics when performing the same ADL with the standard product. This comparison might be useful to contribute to a better assessment of ADs depending on the pathologies or impairments that they are intended to supplement with their use, and it can also be helpful to understand ADs users' reasons for rejection. In addition, the study of these effects may be useful during the process of designing new products intended to improve the daily living of patients with specific pathologies.

5.3.2 Materials and methods

Twelve healthy right-handed subjects (6 male, 6 female; age 35±9.17 years) volunteered to participate in the experiment, approved by the Universitat Jaume I ethical committee (UJI-27/05/15-DPI201452095P). The subjects were previously informed about the characteristics of the experiment and gave their written consent.

Selection of tasks and material

The different typologies of commercially available ADs for grasping were studied (such as personal care, dressing, eating or drinking) and 17 products were chosen to be representative of those intended to solve hand mobility or strength limitations during product manipulation. Then, according to these ADs, 11 ADLs associated with their use were selected. Table 5.3.1 presents the list of specific tasks and products selected and the body posture during each task performance. Tasks were carried out with the normal products and with one, two or three ADs (Figure 5.3.1). Design characteristics of each assistive device are presented in Table 5.3.2.

Table 5.3.1: ADLs performed in the experiment, products used (NP: normal product, AD: assistive device) and body posture during their performance.

ID	TASK	PRODUCTS	POSTURE
T1	Opening cans	1 NP, 1 AD	Sitting
T2	Unscrewing a bottle top	1 NP, 2 ADs	Sitting
T3	Pouring from a bottle	1 NP, 1 AD	Sitting
T4	Pouring from a carton	1 NP, 1 AD	Sitting
T5	Drinking from a glass	1 NP, 1 AD	Sitting
T6	Eating with a spoon	1 NP, 3 ADs	Sitting
T7	Eating with a fork	1 NP, 3ADs	Sitting
T8	Carrying a dish	1 NP, 1 AD	Standing
T9	Using a tap	1 NP, 1 AD	Standing
T10	Brushing teeth	1 NP, 1 AD	Standing
T11	Sliding a zip up	1 NP, 2 ADs	Standing

Three scenarios were prepared (Scenario 1: A chair with the objects to perform the dressing tasks; Scenario 2: A table with the objects to perform the eating/drinking tasks; Scenario 3: A sink and a table with the objects to perform the self-care tasks). The objects were arranged in the same position for all the subjects, and the initial and final postures of each subject were controlled to ensure they were the same (hands and arms relaxed when standing, and with their hands lying relaxed on the table with the palm down when sitting).

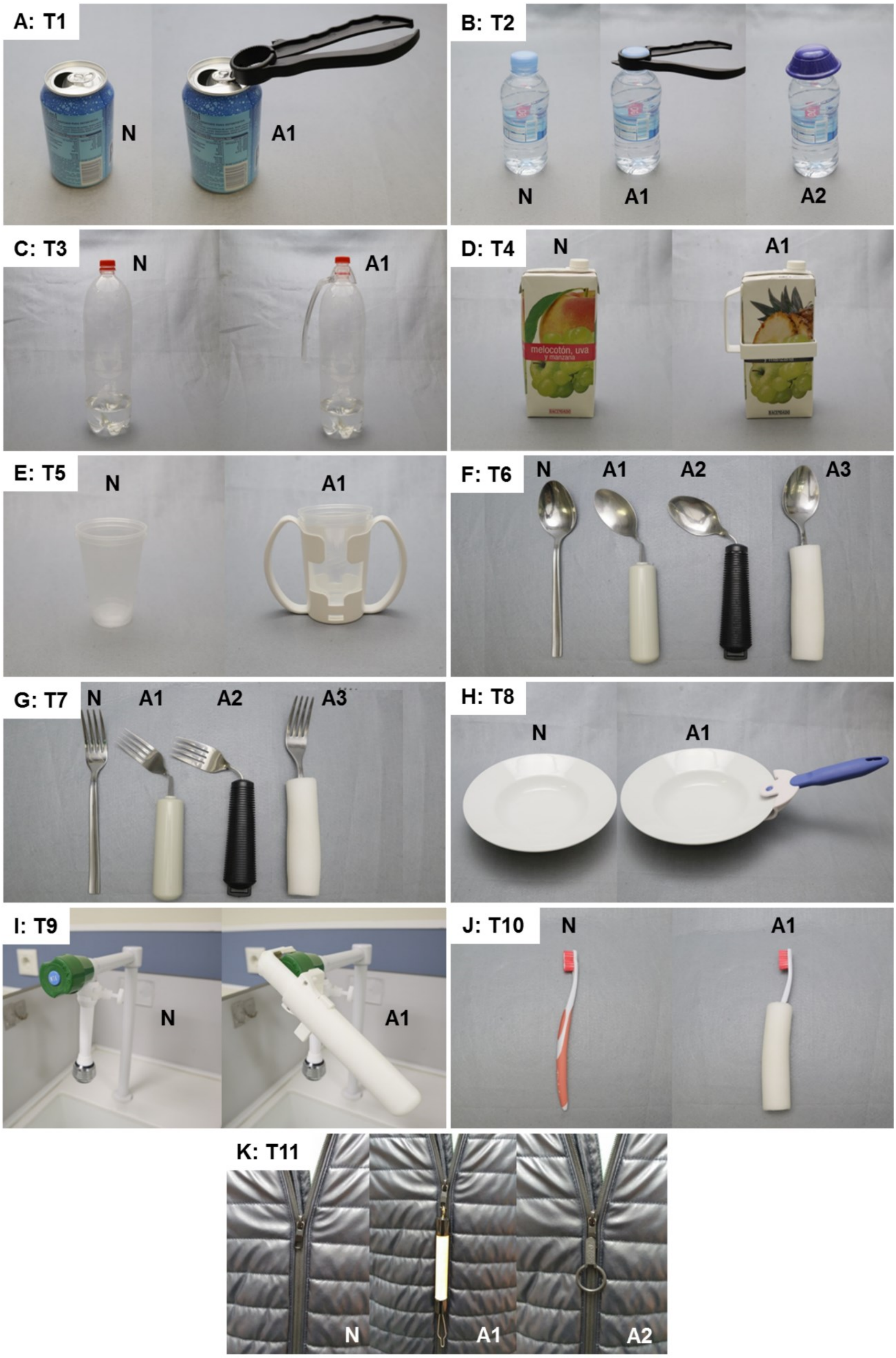


Figure 5.3.1: Products used during the performance of the ADLs (tasks (A) T1 to (K) T11) considered in the experiment. The labels A1, A2 and A3 refer to the different assistive devices used for the task; the label N refers to the normal product.

Table 5.3.2: Design characteristics of the assistive devices used in each task.

TASK	PRODUCT	CHARACTERISTICS
T1	A1	Handle to apply higher torque and reduce precision requirements when pulling the tin ring.
T2	A1	Additional handle to apply higher torque.
	A2	Rubber cap over the original cap, to improve grip.
T3	A1	Vertical additional handle to the bottle.
T4	A1	Vertical additional handle to the carton.
T5	A1	Vertical additional handles (both sides) to the glass.
T6, T7	A1	Thickened and bended plastic cylindrical handle (Ø=30mm, bent angle=40º).
	A2	Thickened and bended rubber conical handle. ($Ø_1$=33mm, $Ø_2$=24mm bent angle=60º)
	A3	Thickened sponge cylindrical handle (Ø=30mm).
T8	A1	Horizontal additional handle to the dish (section 31mm×24mm).
T9	A1	Additional handle to apply higher torque (section 35mm×25mm).
T10	A1	Thickened sponge cylindrical handle (Ø=30mm).
T11	A1	Cylindrical extension of the original zip (Ø=16mm).
	A2	Toroidal extension of the original zip.

Experiment

The subjects performed all the tasks wearing an instrumented glove CyberGlove® (CyberGlove Systems, San José, CA, USA) on their right hand (Figure 5.3.2), and 16 hand joint angles (described in caption of Figure 5.3.3) were recorded. The tasks were performed with both hands when needed, although the products were always used with the right hand. The order of the tasks for each subject was randomized. In all, 336 (12 subjects x 28 products) continuous records (acquired at a frequency of 100 Hz) of 16 gauges were the data collected while performing the tasks. Note that each record had a different duration.

Figure 5.3.2: Subject wearing the instrumented glove performing the task of eating with a spoon.

Data analysis

A previously validated protocol [23] was used to calculate 16 hand joint angles from the gauge data recorded by the CyberGlove. The angles were then low-pass filtered (2nd order Butterworth filter, cut-off frequency 5 Hz). After that, initial and final data of each record (while there was no movement detected) were discarded and the instant velocity computed. For each record and for each joint angle, four parameters were computed: mean angle, ROM (calculated from percentiles 5 to 95 of joint angles), median velocity and percentile 95 of velocity. The time taken to accomplish each task with each product was also computed. Repeated measures ANOVAs (16 joint angles × 4 parameters × 17 ADs) were then performed to check for significant differences while using the normal product and each of the ADs for the same task. The factor for the ANOVAs performed was the product, and the dependent variable was the kinematics parameter (mean angle, the ROM, the median velocity and the P95 velocity) for each joint angle

5.3.3 Results

Regarding the analysis of postures, Figure 5.3.3 presents the mean of the angles at each joint when performing the tasks with normal products and different ADs. Significant differences from the repeated-measures ANOVAs (bilateral asymptotic sig. ≤ 0.01) while performing tasks with normal products (N) and the different ADs available (A1, A2 and A3) are marked in each joint.

Joints studied were: thumb interphalangeal joint (IP1), carpometacarpal joint of thumb (CMC1), metacarpophalangeal joints (1 to 5, thumb to little digits) (MCP1 to MCP5), palmar arch (PalmAr), proximal interphalangeal joints (2 to 5, index to little digits) (PIP2to PIP5), abduction between index and middle fingers (MCP2-3_A), abduction between middle and ring fingers (MCP3-4_A), and abduction between ring and little fingers (MCP4-5_A).

In addition, Figure 5.3.4 presents the mean values of the ROM of each joint obtained when performing each task with normal products and each AD, where significant differences are also marked. Tables of mean values and standard deviation of mean postures and ROM when performed with normal products and ADs are presented as supplemental files (Appendix V).

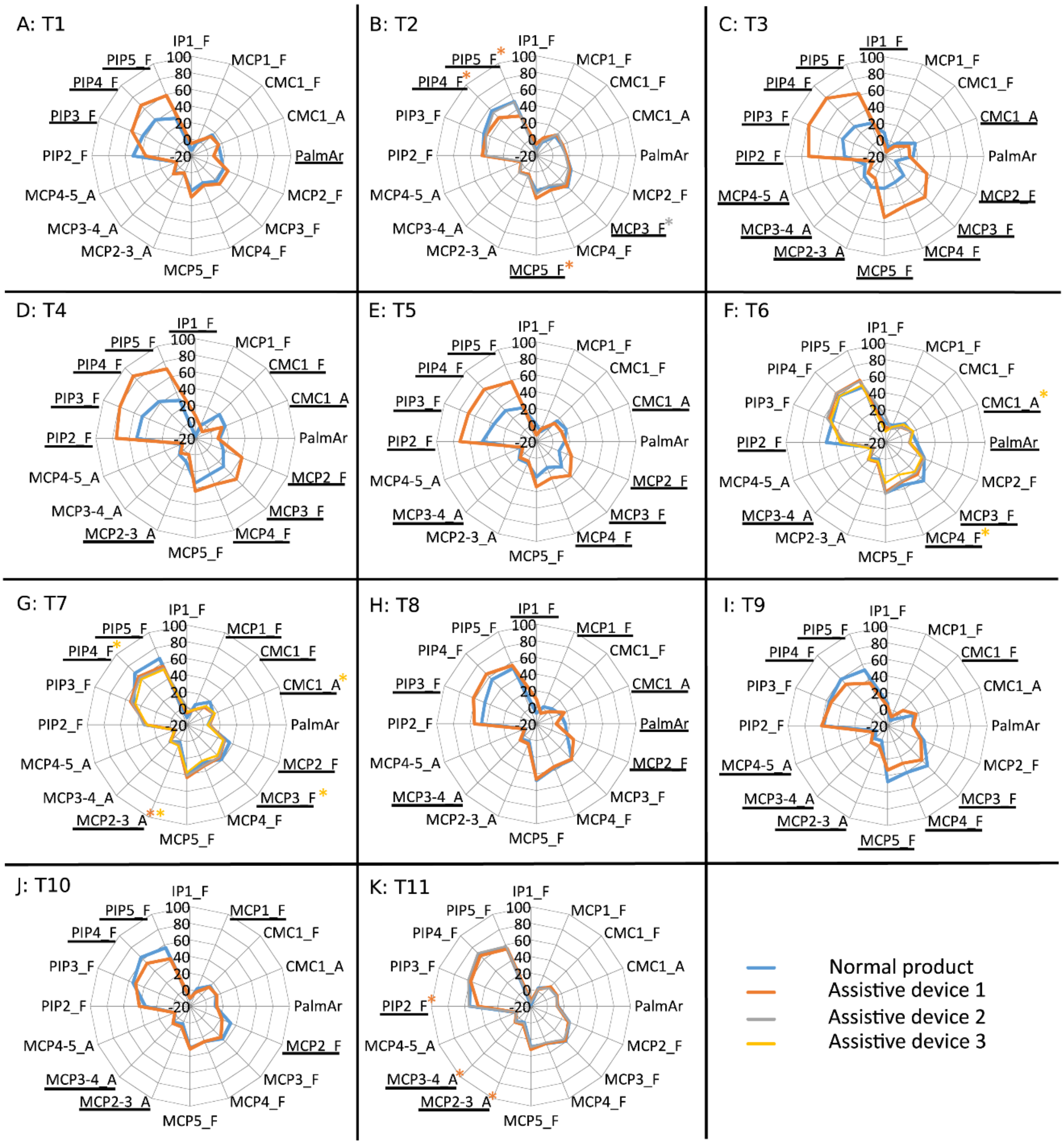


Figure 5.3.3: Mean values of the mean angle (deg) obtained for each joint, task ((A) T1 to (K) T11) and product. Joints with significant differences for all the ADs are underlined. Joints with significant differences for some ADs are underlined and marked with an asterisk of the corresponding colour. Tasks and products labelled as described in Table 5.3.1 and Figure 5.3.1. Joints labelled as described in main text. Positive values for flexion, abduction of fingers and palmar deviation of thumb.

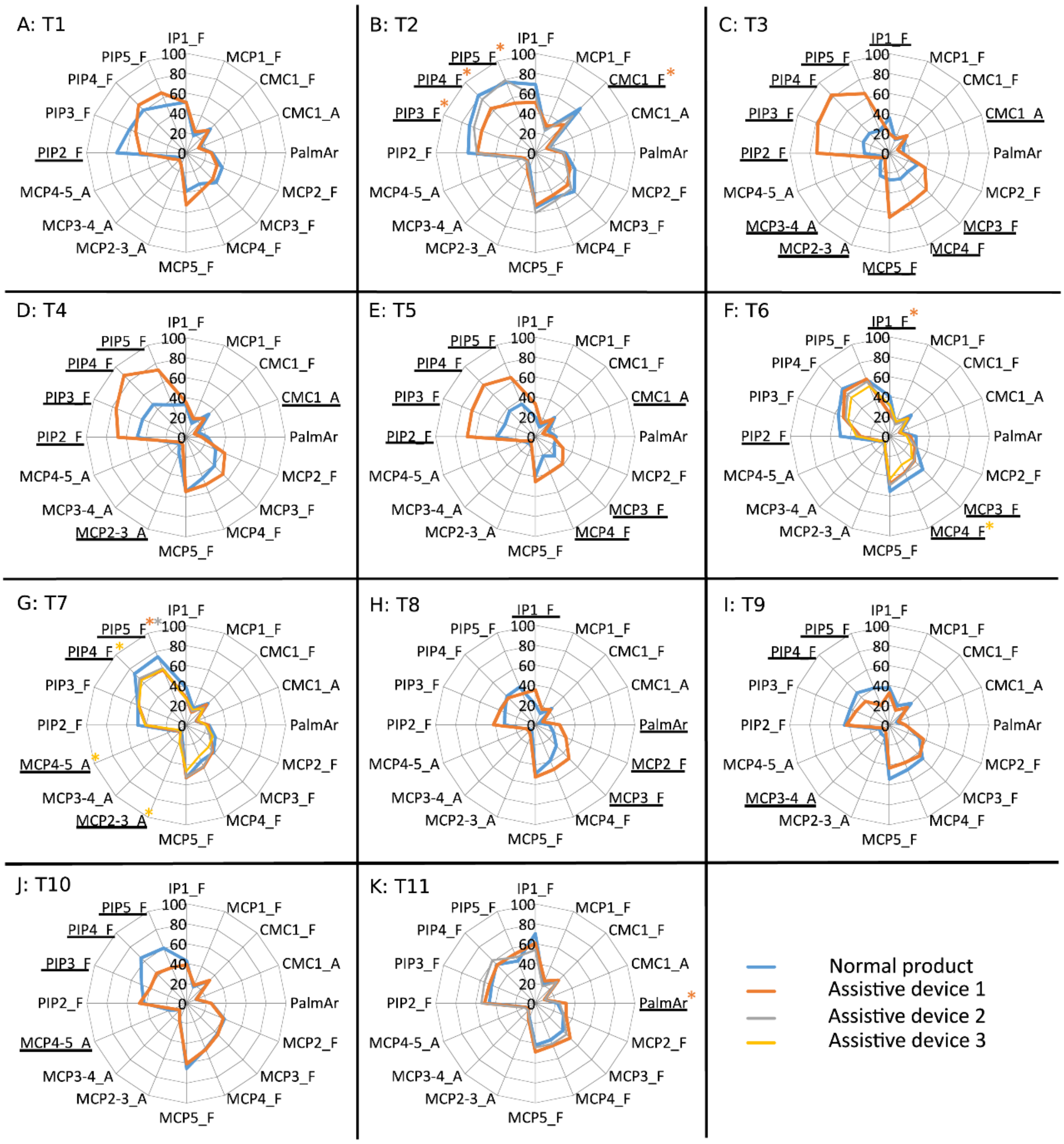


Figure 5.3.4: Mean values of the ROM (deg) obtained for each joint, task ((A) T1 to (K) T11) and product. Joints with significant differences for all the ADs are underlined. Joints with significant differences for some ADs are underlined and marked with an asterisk of the corresponding colour. Tasks, products and joints labelled as described in Figure 5.3.3.

Significant differences in posture and ROM are found in all the ADs analyzed, except for ROM of the bottle opener A2 (T2) and mean posture and ROM of the zip adapter A2 (T11). It can be observed that all the joint angles are affected by the use of some of the ADs.

Regarding the analysis of velocities, Figure 5.3.5 presents the mean values of the median velocities at each joint obtained when performing the tasks with normal products and ADs, and Figure 5.3.6 presents the mean values of the P95 in the same way. Significant differences (bilateral asymptotic sig. ≤ 0.01) found in the repeated-measures ANOVAs are marked in both figures. Tables of mean values and standard deviation of median velocities and peak velocities when performed with normal products and ADs are presented as supplemental files (Appendix V).

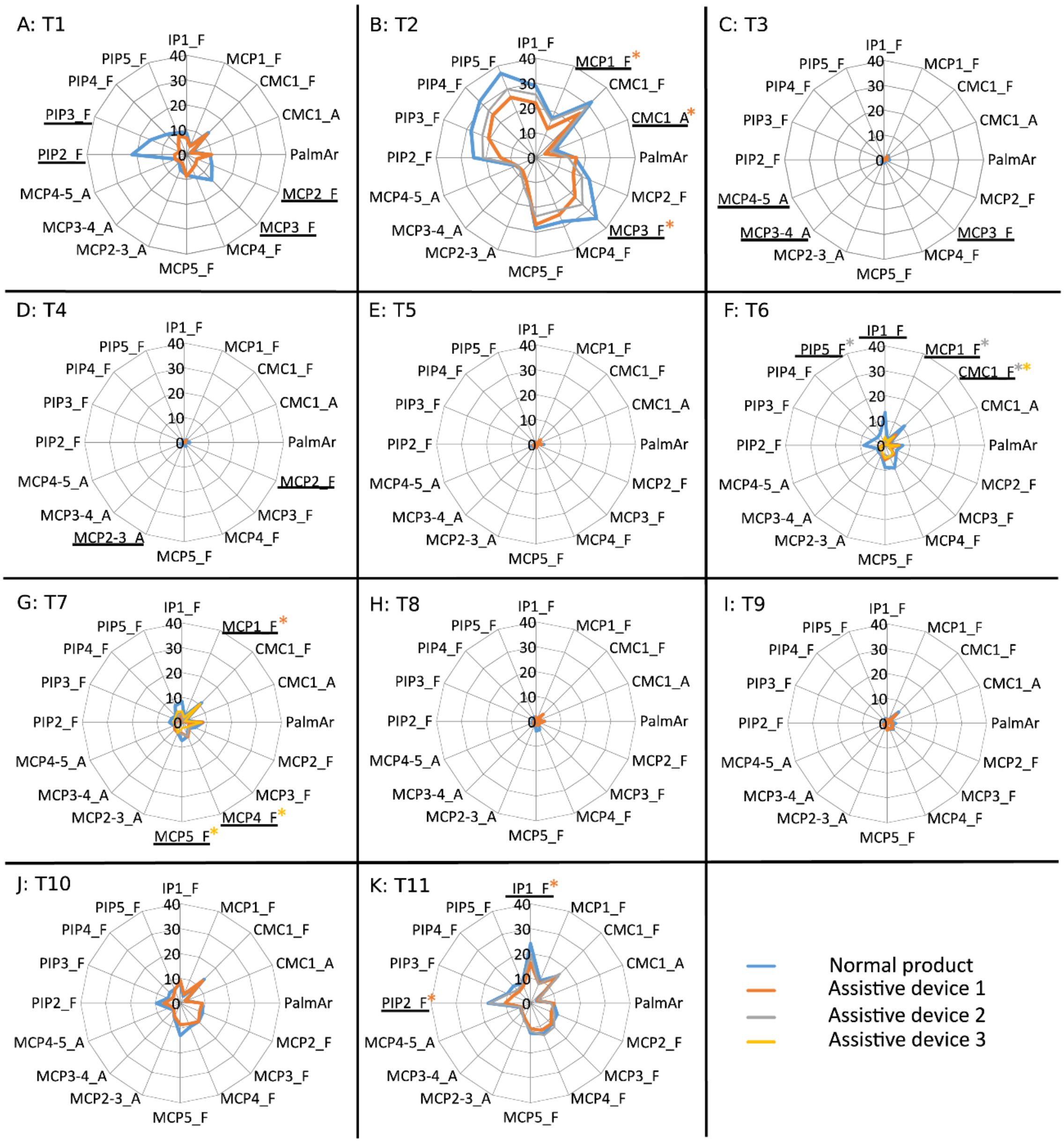


Figure 5.3.5: Mean of the median velocity (deg/s) obtained for each joint, task ((A) T1 to (K) T11) and product. Joints with significant differences for all the ADs are underlined. Joints with significant differences for some ADs are underlined and marked with an asterisk of the corresponding colour. Tasks, products and joints labelled as described in Figure 5.3.3.

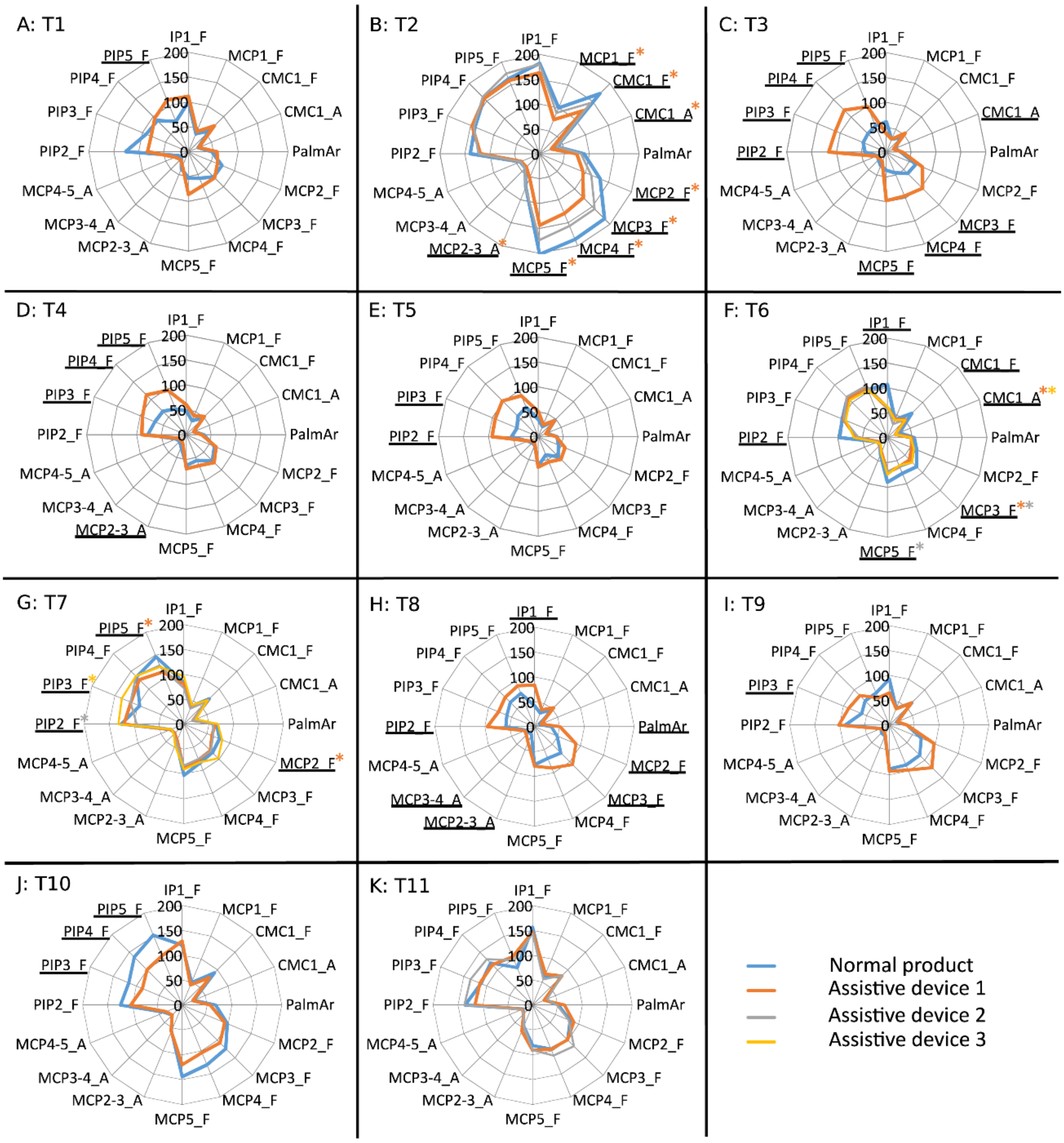


Figure 5.3.6: Mean values of the percentile P95 values of velocities (deg/s) obtained for each joint, task ((A) T1 to (K) T11) and product. Joints with significant differences for all the ADs are underlined. Joints with significant differences for some ADs are underlined and marked with an asterisk of the corresponding colour. Tasks, products and joints labelled as described in Figure 5.3.3.

In general, all the significant differences found in median velocity imply a reduction, and differences are obtained for almost all joints and movements.

Figure 5.3.7 shows the box-and-whiskers plot of the time of accomplishment of each task when performed with the normal product and with the different ADs.

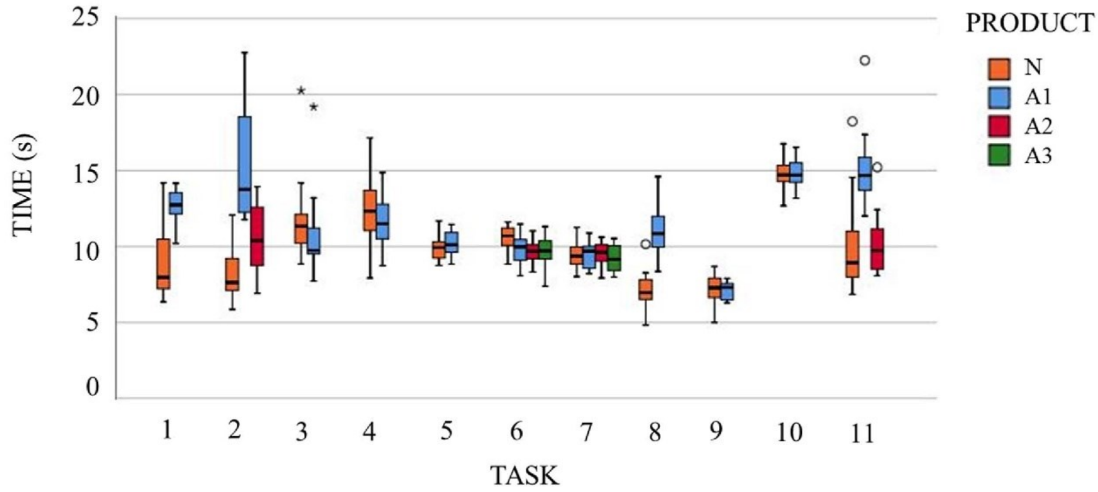


Figure 5.3.7: Box-plots of time of accomplishment of the tasks when performed with the different products. Tasks and products labelled as described in Table 5.3.1 and Figure 5.3.1.

After applying a repeated-measures ANOVA to the time of accomplishment, significant differences (bilateral asymptotic sig. ≤ 0.01) are found for the tasks of opening a can (T1), unscrewing a bottle top (T2), pouring from a bottle (T3), eating with a spoon (only for A2 and A3) (T6), carrying a dish (T8) and sliding a zip up (T11) (only for the A1 adapter). It can be observed that the time of accomplishment in all of these tasks with differences is far higher when performed with ADs except for the task of pouring from a bottle and eating with a spoon.

5.3.4 Discussion

Firstly, in order to assess the goodness or disadvantage of the effects observed in the posture analysis, it is important to analyze whether they favor using a more neutral or awkward (extreme) posture. In this sense, the significant increase in flexion at the thumb interphalangeal (IP) joint by some of the ADs considered leads to a more comfortable posture, as they allow the user to move away from a posture that is too extended. In fact, in some pathologies, such as stroke, the subject finds it difficult to perform digit extension, and this is considered as an indicator of recovery [255]. The observed increase in flexion in proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joints in tasks such as pouring from a bottle (T3), pouring from a carton (T4) and drinking from a glass (T5) is more critical than that observed in tasks like opening a can (T1), since the mean postures used with the ADs are far less neutral in the first ones. Looking at finger abduction, the tap adapter (T9) generates an increase in abductions of fingers index to little, while the bottle adapter (T3) gives rise to a reduction. An increase in abduction between middle and ring fingers when using the AD spoons (T6) and between index and middle fingers when using the adapted forks A1 and A3 (T7) is also observed. Nevertheless, these increases may not imply any negative effect since in all cases the joint angles when using ADs are lower than 10 deg. In particular, the use of the AD for the task of using a tap (T9) solves the negative abduction values required with a normal product, which implies a less neutral posture. The significant differences obtained for the thumb flexion show coordination between the MCP and carpometacarpal (CMC) joints. Looking at flexion of the palmar arch and the thumb CMC joint, significant differences always correspond to a decrease in these joint angles when using the ADs, except for the tap adapter (T9). This can be attributed to the general thickening of the handles in ADs and the shape modulation function of the palmar arch during grasping [256], which is translated into more neutral postures for this joint complex.

The ROM results allow the posture analysis to be completed. Although significant differences are found for the ROM when using any of the ADs, fewer joint angles are affected in comparison to those affected when looking at mean postures. For the analysis, it is important to have in mind that high ROM values make manipulation difficult in patients with reduced hand mobility. Some of the ADs decrease the ROM of all the joints that are significantly affected: the can opener (T1), the bottle opener A1 (T2), all the AD spoons (T6), the AD forks A1 and A2 (T7), the tap adapter (T9) and the toothbrush adapter (T10). On the other hand, the differences obtained when using the dish adapter (T8) and the zip adapter A2 (T11) only imply increases in the ROM. And other ADs increase the ROM at some joint angles while they decrease it at others. However, these increases are not critical when looking at the final ROM values used with the ADs, except for pouring from a bottle (T3), pouring from a carton (T4) and drinking from a glass (T5), which may be a problem for patients with pathologies presenting reduced mobility, such as osteoarthritis or rheumatoid arthritis.

A detailed analysis by task allows us to identify some groups of tasks providing similar posture outcomes. On the one hand, it can be clearly seen that there is an increase in flexion of all the PIP joints when using the bottle adapter (T3), the carton adapter (T4) and the glass adapter (T5), with higher flexion ROM at the PIP joints, and lower abduction ROM at the thumb CMC joint. These results are coherent since all these adapters consist of adding a handle to the objects to be grasped, thus reducing the effective grasping diameter (a handle is grasped instead the object itself). On the other hand, all the spoons (T6) present lower flexion of the palmar arch, middle MCP and index PIP joints, and higher abduction between middle and ring fingers, along with ROM reduction of flexion at the middle MCP joint and index PIP joint. Furthermore, all the forks (T7) reduce the flexion of the thumb MCP, thumb CMC, index MCP and little PIP joints and forks A1 and A3 increase the abduction between index and middle fingers, thereby reducing the ROM of flexion of little PIP joint. The results obtained for the spoons are coherent with previous works focused on the effect of spoon handle diameter on ROM, finding that performing feeding tasks with spoons with thicker handles required lower ROM [144]. Owing to the similarity of the handles of the AD spoons and that of the AD toothbrush (and also the similarity of the grasp performed in both tasks), it can be extrapolated that for this product a lower ROM would also be required, which is also coherent with the results obtained.

A detailed analysis of velocities by task reveals two groups of products with clear patterns of changes that can be associated to their shape and design. The first group, composed of products with designs that add additional handles to products that initially did not have one (or significantly extend the existing ones), shows a general increase in peak velocities: the dish adapter (T8) (additional horizontal handle) or the tap adapter (T9) (additional handle to apply higher torque). Another finding worth noting is the increase in the peak velocity produced by those products with additional vertical handles (bottle adapter (T3), carton adapter (T4) and glass adapter (T5)) on almost all the PIP joints. Conversely, for the products with designs that involve thickened handles (AD spoons (T6) and toothbrush (T10)), or just a wider hand opening (bottle opener A1 (T2)), a general decrease in peak velocities is observed. It is notable that the decrease in median velocities found when using AD spoons (affecting the flexion rate in thumb IP and CMC) may be produced by the significant decreases obtained in peak velocities of the flexions in almost the same joints (index PIP, thumb IP and CMC). Therefore, a relationship can be established between the product diameter and the peak velocities, owing to the fact that the product diameter to be grasped is generally reduced in the ADs where an additional handle is added (carton, bottle, glass, dish, tap), with the exception of the zip adapter. This relationship is supported by the results obtained from ROM and P95 velocities analysis, and the relationship previously found between ROM and handle diameter. While in products such as the bottle opener A1 (T2), spoons (T6) and toothbrush (T10) a general decrease in ROM and P95 is found, in others such as the dish (T8) (and also in all the PIPs for the bottle (T3), carton (T4) and glass adapters (T5)), a general increase in both parameters is found. Nevertheless, these last tasks were initially found to be performed with almost static grasps, which means that these increases in velocities may take place during the phase of reaching for the product, rather than during manipulation.

It can be observed from Figure 5.3.5 that when using normal products the hand is almost static in some tasks because the movement is being performed by the shoulder, elbow and/or wrist, as in the cases of pouring from a bottle (T3), pouring from a carton (T4), drinking from a glass (T5), carrying a dish (T8) and using a tap (T9). But other tasks present higher median velocity values, especially the task of unscrewing a bottle top (T2), which presents the highest values for all the joints. These median velocities are coherent with the type of grasp and manipulation performed during these tasks (in the aforementioned tasks, static grasps are usually performed, while in the task of opening a bottle a special grasp is performed combined with fine manipulation).

The analysis of velocities requires taking into account the peak velocities (Figure 4.3.6). When using normal products, the highest values of peak velocities correspond to the unscrewing a bottle tap task (T2), and the ADs allow a significant reduction in these peak velocities. In general, the peak velocities of thumb decrease for the tasks of opening a bottle (with A1 opener) (T2) and eating with a spoon (T6), and increase in carrying a dish (T8).

Regarding the MCP flexion, the values also decrease in the tasks of opening a bottle with A1 (T2) and eating with a spoon (T6), and increase when pouring from a bottle (T3) and carrying a dish (T8). The MCP abductions present fewer significant differences, the only remarkable ones being the reduction in the abduction between fingers when using the bottle opener A1 (T2) and the carton adapter (T4) or the increase when using the dish adapter (T8), only the differences found between index, middle and ring fingers being significant. Finally, a general increase in the PIP peak velocities is found in the tasks of pouring from a bottle (T3), pouring from a carton (T4) and drinking from a glass (T5).

As for the time of accomplishment analysis, the increase shown when using ADs can be attributable to the lack of experience of healthy subjects with this type of products. This increase in time of accomplishment is coherent with the general decrease in median velocities observed. Nevertheless, it is remarkable that for the task of eating with the spoons A2 and A3 (T6), apart from being performed in less time with ADs, all the significant differences in median and peak velocities imply a decrease in the values, which can be an indicator of grasp stability. In contrast, in the case of the dish adapter (T8), where time is higher and peak velocities increase significantly in the majority of joints, the smoothness of the movement is clearly lower. In this sense, a smoothness indicator can be determined from the difference between the peak and the median velocities, the lowest differences being taken as more beneficial. Thus, all those tasks with significant decreases in mean velocities and increases in peak velocities – the bottle adapter (T3) and the carton adapter (T4) – will have less movement smoothness. Additionally, low differences between peak and median velocities are observed in tasks such as opening a can (T2), brushing teeth (T10) and using a zip (T11), revealing a smooth operation. Nevertheless, these tasks are already smooth when performed with normal products, so it seems that no AD produces a significant improvement in movement smoothness.

Overall, taking into account all the results of the different parameters and the design of the ADs, a five-group classification of ADs can be established: ADs with additional vertical handles (T3, T4, T5), with additional horizontal handles (T10), with handles to perform higher torques (T9), with extended handles (T11) and with thickened handles (A1 of T2, T6, T7 and T10). Figure 5.3.8 presents an overview of the global results obtained for each group from the different analyses of posture and velocity, as well as a brief example of pathologies that can benefit from the use of these ADs.

It can be observed that the design characteristics that imply the most changes are those with additional (vertical or horizontal) or thickened handles. The ADs that involve more neutral postures and lower velocities than the normal ones are those that have thickened handles or require a wider hand opening for the grasp, such as the bottle opener A1 (T2), the AD spoons (T6), the AD forks (T7) and the AD toothbrush (T10). However, the ones that add handles to products without one (the bottle adapter (T3), the carton adapter (T4), the glass adapter (T5) and the dish adapter (T8)) produce less neutral postures, higher velocities and less smoothness than the normal ones. These results may lead us to identify the latter as more suitable when strength is reduced and a grasp with more flexed PIPs and MCPs is needed in order to ensure that the object is not going to slip from the hand, but not for those patients with reduced hand mobility. Nevertheless, those with thickened handles may be in general more beneficial for all pathologies, especially when hand mobility is reduced, since, in some studies, upper limb ROM analysis was found to allow therapists to assess the abilities of their patients [252], while peak and mean velocity were also commonly used when evaluating post-stroke patients [257]. Smoothness was also identified as an important marker of patients' motor recovery [253], [254], as well as a parameter directly related with users' rating when assessing the use of the product during studies focused on upper limb joints [147]. Thus, in these cases special attention is needed when prescribing ADs to patients with the entire upper limb affected, since some products that help to overcome hand impairments may not be beneficial to the arm joints. Nevertheless, this work is an approach to AD assessment and the design of products and their kinematic implication should be studied individually before prescribing. Different pathologies may present different impairments such as reduced strength. In these cases, products with additional and thinner handles, despite increasing ROM or leading to less neutral postures, may be making performance of the task easier.

Finally, it has to be highlighted that the instrumented glove may introduce some loss of dexterity during the task performance that could have slightly affected the time of accomplishment of the tasks and also hand kinematics. Nevertheless, this loss of dexterity affects both the standard and the adapted product equally and, therefore, the comparison during the use of both types of products is valid. In addition, the experiments have been carried out on healthy subjects and may not reveal some of the difficulties experimented by patients during the performance of the tasks, but it was thought to be representative of the required kinematics under the best conditions. Performing more studies on subjects with specific pathologies may be useful in order to explore the similarity of results between healthy subjects and different pathologies. Moreover, it may reveal more accurate, but less general, effects.

	Vertical additional handles 	**Horizontal additional handles** 	**Handles to apply higher torques** 	**Extended handles** 	**Thickened handles /handles requiring wider hand opening** 
Mean posture	Increase in PIPs and MCPs flexion	Increase in middle-ring abduction. Increase in flexion of thumb IP and decrease in thumb MCP	Increase in abductions of fingers index to little, decrease in MCPs flexion	Almost no differences	General decrease in PIPs and MCPs flexion (except for some exceptional increase)
ROM	Increases in PIPs and MCPs	Increases	Decrease in PIPs flexion	Few differences (mainly increases)	Decreases in PIPs
Median velocity	Decreases	No differences	No differences	Almost no differences (all decreases)	Decreases
Peak velocity	Increases in PIPs	Increases	Few differences (all increases)	No differences	Decreases (except for middle PIP3 with forks)
Smoothness	Decreases	Decreases	No differences	Increases	Increases
Pathologies	Pathologies with mainly grip strength loss: Carpal tunnel syndrome, muscle dystrophy or muscle atrophy	Pathologies with CMC involvement: Rhizarthrosis	Every pathology, especially when strength is reduced: Carpal tunnel syndrome, muscular dystrophy or muscle atrophy	Every pathology, especially when precision in fine manipulation is affected: Stroke, cerebral palsy	Pathologies with reduced hand mobility: Osteoarthritis or rheumatoid arthritis

Figure 5.3.8: AD design characteristics and global results obtained across the different studies.

5.3.5 Conclusions

A detailed objective study of how hand kinematic parameters of healthy hands are affected when using different ADs during the performance of given tasks has been provided. Knowing how healthy hands are affected may help determine the most suitable ADs for a patient depending on the limitations derived from the pathology or the difficulties reported on daily living. The appropriateness of each AD has been shown to depend on the joints affected by the pathology, as not all the products affect the same joints in the same way, and they can reduce the ROM or improve mean postures for some joints, but lead to higher ROM or less neutral postures in others. Furthermore, an overview of the effects from using the ADs depending on the handle design has been provided, which makes the selection task considerably easier, thereby allowing therapists to prescribe the ADs objectively in a faster way. Moreover, this information about handle design implications could also be used by the AD manufacturers in order to ensure a better use of their products by establishing recommendations and precautions for use.

5.4 Conclusions

ADs prescription process is an essential part of a successful rehabilitation therapy, and results drawn from the studies corroborate it. As concluded from the first study, not all the products may be suitable for all the pathologies, as some of them were observed to require less neutral upper limb postures. These findings were also supported by the results from the second study presented in this chapter, where it was obtained that some ADs lead to less neutral hand joint postures or require wider range of movement, what becomes unachievable for patients with some pathologies.

These works only gave a glimpse on how design parameters can affect upper limb behaviour. In this case, only relationship between product design and quantifiable effects such as hand posture, upper limb posture and hand kinematics were studied. Nevertheless, other quantifiable parameters such as grip strength may be affected and could gave interesting points of view regarding the effects observed, as well as complementing the ones here observed. Furthermore, in the studies presented only product shape was considered as a design parameter when classifying products in order to correlate them with the results observed. However, other parameters such as product weight or material rugosity for sure play an important role in the observed effects.

There is still a long way to go in the study of the effect of ADs design in upper limb behaviour. Notwithstanding, with these studies it was observed that AD design effects can be quantifiable, and a key tool for assisting therapists during ADs selection process, as well as product designers, has been given. Specifically, these quantifiable parameters become very valuable data for product designers, as they may help them to develop pathology-specific AD designs, as well as universal design solutions which would benefit the whole users' community, independently of their impairment.

Chapter 6

Conclusions

The main purpose of this thesis was to contribute to the characterisation of hand kinematics during product manipulation in ADLs. This aim was composed of three main objectives: (i) validating the use of instrumented gloves as a motion capture system, (ii) characterising hand kinematics using posture and velocity-related parameters, identifying task groups requiring extreme postures or velocities, and creating a large dataset of hand kinematic data during ADLs to this purpose , and (iii) analysing the effect of assistive devices (ADs) on hand and upper limb kinematics using qualitative and quantitative kinematic parameters. In order to achieve these objectives, (i) several experiments of validation of different usage aspects of instrumented gloves were carried out, in order to study aspects such as their effect on manual skills or the feasibility of using them to measure distal interphalangeal joints, among other aspects. Moreover, (ii) a large dataset of kinematic data collected using instrumented gloves on both hands of a representative sample of healthy subjects performing realistic ADLs using a wide variety of products was created, analysed and published, making it available to the research community. Furthermore, (iii) experiments using normal products and ADs were performed, in order to study the effect of ADs design on grasp types performed and arm posture (using visual analyses) and on hand joint kinematics (using an instrumented glove). All the outcomes from these experiments have been published in international journals or conferences, or are about to be submitted for review, contributing to the biomechanics and ergonomics fields in three main lines: (A) Contributions to validation of instrumented gloves for motion capture; (B) Contribution to hand kinematics characterisation; (C) Contributions to the effect of ADs on hand and upper limb kinematics.

A. Contributions to the validation of instrumented gloves for motion capture

A1. On their effect on manual skills

After performing dexterity tests requiring different levels of precision while wearing the instrumented gloves CyberGlove and also in bare-handed conditions, manual skills were found to decrease when wearing CyberGlove. This observed reduction may affect hand kinematic parameters such as velocities. The scores obtained in the test evaluating fine motor skills decreased by an average of 29%, while the scores obtained on those evaluating gross motor skills and capability to perform activities of daily living were reduced by an average of 8% and 3%, respectively. Then, instrumented gloves are mostly recommended when performing tasks requiring medium and gross motor skills. Nevertheless, these observed reduction rates could be used to adjust dexterity test scores when performed while wearing instrumented gloves. Note that the experiments were performed using a CyberGlove of 18-DoF, which has uncovered fingertips. Therefore, the effects on manual skills are expected to be higher when using the 22-DoF model, which has covered fingertips.

A2. On the feasibility of using gloves to measure distal interphalangeal joints

Instrumented gloves measuring distal interphalangeal joints (as the CyberGlove 22-DoF) are longer in order to allocate the additional sensors. Several experiments were performed to check the goodness of this glove model to record ADLs performance during product manipulation in a sample of subjects with different hand lengths. In these experiments some subjects reported that these big-sized gloves hindered manipulation due to improper fit to their hands. This improper fitting also lead to inaccurate data collection, as in some subjects with medium-small hand length the extensiometric gauges measuring PIP joints also covered DIP joints, providing cumulative flexion data of both joints altogether. In other cases, extreme DIP extensions were recorded because the glove fingertips did not fit subjects' fingertips, which bent when contacting the manipulated object. For this reason, their use should be limited to big-sized hands (at least 184 mm long), therefore not being adequate to study the kinematics of a sample of subjects intended to be representative of adult population regarding hand sizes and gender. Usability of instrumented gloves could be significantly improved if two or three different glove sizes were commercially available, or if position/size of gauges is reconsidered and thinner materials used to tailor the main body of the glove.

A3. On using PIP joint angles to estimate DIP ones

Estimating DIP joint angles from PIP ones (to avoid the above-stated problems) has been assessed. Several experiments were carried out, by considering both free motion and product manipulation tasks. DIP and PIP angles were observed to present a high correlation during free motion tasks, but not during manipulation. Regression coefficients assuming linear relationship between PIP and DIP angles were calculated for each finger, both from free motion data recordings and from product manipulation recordings, thus obtaining two different sets of coefficients for each finger. Then, the error arisen when estimating DIP joint angles using both sets was calculated and compared. It was observed that the estimation using the coefficients obtained from free motion tasks provided low absolute errors only in grasps or tasks where both PIP and DIP were highly flexed. Using coefficients from manipulation tasks provided lower mean absolute error per task than using the free motion ones, but they failed to provide accurate estimations in cases with passive extension of DIP joints while PIP is flexed (when pressure is applied during grasping of objects). Thus, errors when estimating DIP from PIP angles are highly dependent on the task and grasp type performed, owing to passive extensions and to the fingers adaptation to the object shape. Therefore, it is only recommended estimating DIP joint angles from PIP ones in case of studying free motion or grasps where both joints are highly flexed and using coefficients obtained in free motion, but not in other conditions. For this reason, providing DIP angles as estimations from the PIP ones during product manipulation experiments carried out in this thesis was discarded. Nevertheless, future works may address the estimation of DIP angles by considering kinematic synergies.

A4. On the use of instrumented gloves to automate the distinction between free motion and manipulation phases

In order to automatically distinguish free motion from product manipulation phases when recording ADLs experiments, an instrumented glove (Virtual Motion Glove 30 (VMG30)) equipped with pressure sensors and extensiometric gauges was used. After performing several grasping experiments using VMG30 and CyberGlove, the difference in the accuracy of distinguishing free motion from manipulation with visual analysis (when using CyberGlove) or using the data from VMG30's pressure sensors was not statistically significant. Furthermore, kinematic recordings using this glove were not as accurate as the CyberGlove ones. Apart from this, subjects participating in the experiment reported that VMG30 was too bulky and hindered manipulation, owing to the required wiring to equip it with pressure sensors and also extensiometric gauges. Therefore, using it for the product manipulation experiments of this thesis was discarded. Nevertheless, using a glove with pressure sensors could be a useful alternative in experiments where visual analysis is not possible, as well as using complementary devices to measure pressure contact along with CyberGlove. That said, VMG30 needs a redesign to reduce its wiring and bulkiness before being used in product manipulation experiments.

B. Contributions to hand kinematics characterisation

B1. On the creation of a large dataset of kinematic data in feeding and cooking ADLs

A gap was observed in hand kinematics datasets of both hands while performing ADLs regarding certain aspects such as the number of products used, the variety of tasks performed, the freedom to perform the tasks, the number of subjects recruited or the anatomical angles recorded, among others. For this reason, the KINE-ADL BE-UJI Dataset was created and made publicly available in an open repository. This dataset contains a total of 1160 recordings with anatomical angles of both hands of 20 healthy subjects during the performance of feeding and cooking ADLs. Some of the strengths of this dataset are: the wide variety of objects used (66 objects), the in-depth study of representative feeding and cooking tasks (58 tasks, divided into 178 actions), the freedom given to the subjects to perform the tasks, the fact of recording both hands and the type of data provided (continuous recording of 18 anatomical angles per hand, collected at a frequency of 100Hz). This dataset intends to contribute to hand kinematics characterisation, as well as to the fields of artificial intelligence and product design, and it has been key for the analyses lately performed in the thesis.

Even though the dataset only contains feeding and cooking tasks, the intention is to progressively add data from other fields of ADLs, in order to enlarge the dataset.

B2. On the characterisation of hand kinematics in feeding and cooking ADLs

In order to deepen in the characterisation of hand kinematics during product manipulation in ADLs, tasks from the previous dataset were classified into thirteen task groups, depending on task features (force type and intended motion) considered in a grasp taxonomy for everyday actions [12]. For each task group, kinematic data of both hands was analysed by means of postural and velocity-related parameters, aiming to fill the gap in hand joint velocity analyses during a wide variety of ADLs using products with different shapes. Furthermore, the use of a manipulability index was proposed, providing information regarding the percent of time where joint velocity was above 10 deg/s. Apart from providing normative values of kinematic parameters for healthy hands, these analyses helped to identify the task groups that require more extreme postures, higher velocities and higher levels of manipulability, such as using cutlery and kitchen utensils, transportation and manipulation of large objects, opening packages, unscrewing/screwing caps or cleaning. Therefore, developing and using ADs to perform these tasks when user's hand function is affected would be advisable.

C. Contributions to the effect of ADs on hand and upper limb kinematics

C1. On their effect on grasp types and arm posture

In order to analyse the effect of ADs on grasp types and arm posture, healthy subjects were recorded in video while performing a set of ADLs using normal products and ADs with different design characteristics. Grasp types, parts of the hand contacting the object, time of performance and arm postures (shoulder, elbow and wrist) were visually analysed from the videos and classified. Among other outcomes, it was observed that the use of ADs increased the frequency of power grasps. Precision grasps were less frequent than power grasps when using ADs with thickened handles, but less neutral postures of the arm were observed. These results may be explained by the use of less neutral arm postures to compensate for the lack of precision of the power grasps. Therefore, even though they lead to the performance of power grasps (which are more suitable when hand function is affected), they have a questionable effect on arm posture.

C2. On their effect on hand joints kinematics

After performing a set of ADLs using normal products and ADs while wearing an instrumented glove in the right hand, it was observed that not all the products affected the same joints in the same way. A specific assistive device can reduce the required range of motion (ROM) or improve mean postures for some joints, but lead to higher ROM or less neutral postures in other joints.

Depending on the modification performed in products design, the effects observed in kinematic parameters and the pathologies that might benefit of using these products are the ones presented in Figure 6.1.1.

	Vertical additional handles 	**Horizontal additional handles** 	**Handles to apply higher torques** 	**Extended handles** 	**Thickened handles /handles requiring wider hand opening** 
Mean posture	Increase in PIPs and MCPs flexion	Increase in middle-ring abduction. Increase in flexion of thumb IP and decrease in thumb MCP	Increase in abductions of fingers index to little, decrease in MCPs flexion	Almost no differences	General decrease in PIPs and MCPs flexion (except for some exceptional increase)
ROM	Increases in PIPs and MCPs	Increases	Decrease in PIPs flexion	Few differences (mainly increases)	Decreases in PIPs
Median velocity	Decreases	No differences	No differences	Almost no differences (all decreases)	Decreases
Peak velocity	Increases in PIPs	Increases	Few differences (all increases)	No differences	Decreases (except for middle PIP3 with forks)
Smoothness	Decreases	Decreases	No differences	Increases	Increases
Pathologies	Pathologies with mainly grip strength loss: Carpal tunnel syndrome, muscle dystrophy or muscle atrophy	Pathologies with CMC involvement: Rhizarthrosis	Every pathology, especially when strength is reduced: Carpal tunnel syndrome, muscular dystrophy or muscle atrophy	Every pathology, especially when precision in fine manipulation is affected: Stroke, cerebral palsy	Pathologies with reduced hand mobility: Osteoarthritis or rheumatoid arthritis

Figure 6.1.1: AD design characteristics, observed effects in kinematic parameters and pathologies that might benefit of using these products.

C3. On their prescription for specific pathologies

The results from both experiments using ADs highlight the importance of selecting the appropriate AD depending on the pathology. In the first work it was remarked that it was important to distinguish between ADs compensating for a lack of grip strength and those compensating for a loss of dexterity, as some ADs might be helping people with reduced hand mobility but leading to extreme arm postures. In the second work, it was observed that not all the ADs affected hand joints in the same way, being highly dependent on a product's design characteristics. Thus, it can be concluded that not all products may be suitable for all pathologies. For this reason, the prescription of a specific assistive device should be based on the patient's specific diagnosis and reported limitations, considering the joints affected by the pathology.

Future work

Even though the works presented in this thesis are only a contribution to the field, their outcomes can be key to plan further research. Therefore, in these last paragraphs of the thesis I will focus on providing an overview of the more imminent research lines drawn, which are, mainly, in two directions: (i) widening the studies started in hand kinematics characterisation and (ii) analysing the effect of manipulation ADs in a more holistic way.

One final goal of the characterisation of hand kinematics is the elaboration of design guidelines for AD products. Although hand kinematics is key in the performance of ADLs, force requirements are more limiting in many cases. Therefore, experimental data relating both postural and muscular requirements would help to better characterise healthy hand behaviour. Nevertheless, scarce extensive datasets of synchronised hand postural and muscular data while performing a wide variety of ADLs and using a variety of products can be found in the literature. For this reason, I propose to broaden the KINE-ADL BE-UJI Dataset by introducing data of experiments performing ADLs from other fields not studied yet (e.g. personal care), but also including synchronised muscular activity recordings using wireless EMG sensors recently acquired in the B&E group.

Characterising hand behaviour in a wider variety of tasks would also help to identify new groups of tasks with mobility requirements or muscular activity hardly achievable by people with affected hand function and, therefore, identifying new fields where using ADs would be recommended. Parameters analysed in these characterisations could be broadened, also introducing kinematic and muscular synergies in bimanual tasks, which has been less studied in literature. Furthermore, a deeper study in velocity-related parameters as an indicator of required dexterity would be worthily, as it has been observed that manipulability index has provided an insight. Then, in these specific fields with higher requirements, performing experiments using ADs and normal products with different design characteristics (as different diameters of caps while unscrewing, or different bottle diameters while serving liquids) might provide results similar to those presented in section 5.3 with ADs, but revealing if these kinematic and muscular requirements could be met just using another normal product with a different shape or if using an ADs is the best alternative.

Nevertheless, as mentioned previously, the studies presented in this thesis on the effect of ADs on hand and upper limb kinematics only gave a glimpse of how design parameters can affect upper limb behaviour, because only postural parameters have been analysed. Other parameters such as grip strength may provide an interesting insight into products' characteristic effects on the upper limb. However, these analyses would only assess the functional component of ADs, but would left aside subjective and emotional aspects, which are key in the process of adaptation to the use of an AD. For this reason, the Biomechanics and Ergonomics Group has recently applied for public funding for a research project in this direction, going toward new paradigms based on holistic assessment of ADs. This research line intends to develop and apply methodologies to assess the affective and cognitive aspects of using ADs, apart from the biomechanical ones, which have been partly studied in this thesis. These experiments would comprise studies such as questionnaires, eye-tracking tests, or dexterity tests through cognitive distraction tests, in order to assess the cognitive demand of each AD.

References

[1] WHO, "International Classification of Functioning, Disability and Health (ICF)," 2001. http://www.who.int/classifications/icf/en/ (accessed Sep. 22, 2020).

[2] M. Vergara, J. L. Sancho-Bru, V. Gracia-Ibáñez, and A. Pérez-González, "An introductory study of common grasps used by adults during performance of activities of daily living," *J. Hand Ther.*, vol. 27, no. 3, pp. 225–234, Apr. 2014, doi: 10.1016/j.jht.2014.04.002.

[3] Bureau of Labor Statistics, "American Time Use Survey (ATUS)." https://www.bls.gov/tus/ (accessed Oct. 23, 2020).

[4] M. Vergara, V. Gracia-Ibáñez, and J. L. Sancho-Bru, "Evaluation of Hand Functionality During Activities of Daily Living (ADL): A Review," in *Activities of Daily Living (ADL): Cultural Differences, Impacts of Disease and Long-Term Health Effects*, N. S. P. I. Scott T. Lively, Ed. 2015, pp. 103–131.

[5] A. M. Dollar, "Classifying Human Hand Use and the Activities of Daily Living," in *The Human Hand as an Inspiration for Robot Hand Development*, vol. 95, Springer International Publishing Switzerland, 2014, pp. 201–216.

[6] M. A. Arbib, T. Iberall, and D. Lyons, "Coordinated Control Programs for Movements of the Hand," in *Hand Function and the Neocortex*, Berlin, Heidelberg: Springer Berlin Heidelberg, 1985, pp. 111–129.

[7] M. Jeannerod, "Intersegmental coordination during reaching at natural visual objects," *Atten. Perform. IX*, pp. 153–168, 1981.

[8] M. Jeannerod, "The Timing of Natural Prehension Movements," *J. Mot. Behav.*, vol. 16, no. 3, pp. 235–254, Sep. 1984, doi: 10.1080/00222895.1984.10735319.

[9] R. Tomovic, G. Bekey, and W. Karplus, "A strategy for grasp synthesis with multifingered robot hands," in *Proceedings. 1987 IEEE International Conference on Robotics and Automation*, 1987, vol. 4, pp. 83–89, doi: 10.1109/ROBOT.1987.1087842.

[10] J. M. F. Landsmeer, "Power Grip and Precision Handling," *Ann. Rheum. Dis.*, vol. 21, no. 2, pp. 164–170, 1962, doi: 10.1136/ard.21.2.164.

[11] H. Liu, T. Iberall, and G. A. Bekey, "The multi-dimensional quality of task requirements for dextrous robot hand control," in *Proceedings,*

1989 International Conference on Robotics and Automation, 1989, pp. 452–457, doi: 10.1109/ROBOT.1989.100028.

[12] J. Liu, F. Feng, Y. C. Nakamura, and N. S. Pollard, "A taxonomy of everyday grasps in action," *IEEE-RAS Int. Conf. Humanoid Robot.*, vol. 2015-Febru, pp. 573–580, 2015, doi: 10.1109/HUMANOIDS.2014.7041420.

[13] A. A. Samadani, S. J. Burton, R. Gorbet, and D. Kulić, "Laban effort and shape analysis of affective hand and arm movements," *Proc. - 2013 Hum. Assoc. Conf. Affect. Comput. Intell. Interact. ACII 2013*, pp. 343–348, 2013, doi: 10.1109/ACII.2013.63.

[14] E. Carmeli, H. Patish, and R. Coleman, "The Aging Hand," *Journals Gerontol. Ser. A*, vol. 58, no. 2, pp. M146–M152, Feb. 2003, doi: 10.1093/gerona/58.2.M146.

[15] D. R. Steinberg, "MSD Manuals: Swan-neck deformity." https://www.msdmanuals.com/en-kr/professional/musculoskeletal-and-connective-tissue-disorders/hand-disorders/swan-neck-deformity (accessed May 19, 2021).

[16] J. L. Sancho-Bru, "Model biomecànic de la mà orientat al disseny d'eines manuals," *PhD Thesis*, 2000.

[17] Nursecepts, "9 Facts About the Skeletal System Every Nursing Student Should Know," 2017. https://nursecepts.com/9-facts-about-the-skeletal-system-every-nursing-student-should-know/ (accessed Oct. 05, 2020).

[18] V. Gracia-Ibáñez, M. Vergara, J. L. Sancho-Bru, M. C. Mora, and C. Piqueras, "Functional range of motion of the hand joints in activities of the International Classification of Functioning, Disability and Health," *J. Hand Ther.*, vol. 30, no. 3, pp. 337–347, 2017, doi: 10.1016/j.jht.2016.08.001.

[19] P. Merriaux, Y. Dupuis, R. Boutteau, P. Vasseur, and X. Savatier, "A study of vicon system positioning performance," *Sensors (Switzerland)*, vol. 17, no. 7, pp. 1–18, 2017, doi: 10.3390/s17071591.

[20] J. L. Sancho-Bru, N. J. Jarque-Bou, M. Vergara, and A. Pérez-González, "Validity of a simple videogrammetric method to measure the movement of all hand segments for clinical purposes," *Proc. Inst. Mech. Eng. Part H J. Eng. Med.*, vol. 228, no. 2, pp. 182–189, Feb. 2014, doi: 10.1177/0954411914522023.

[21] E. Maranesi, F. Di Nardo, G. Ghetti, L. Burattini, and S. Fioretti, "A goniometer-based method for the assessment of gait parameters," in *MESA 2014 - 10th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications, Conference Proceedings*, 2014, no. C, doi: 10.1109/MESA.2014.6935539.

[22] M. I. B. Lin, R. H. Hong, J. H. Chang, and X. M. Ke, "Usage position and virtual keyboard design affect upper-body kinematics, discomfort, and usability during prolonged tablet typing," *PLoS One*, vol. 10, no. 12, pp. 1–21, 2015, doi: 10.1371/journal.pone.0143585.

[23] V. Gracia-Ibáñez, M. Vergara, J. H. Buffi, W. M. Murray, and J. L. Sancho-Bru, "Across-subject calibration of an instrumented glove to measure hand movement for clinical purposes," *C. Comput. Methods Biomech. Biomed. Eng.*, vol. 20, no. 6, pp. 587–597, 2017, doi: http://dx.doi.org/10.1080/10255842.2016.1265950.

[24] L. McAtamney and E. Nigel Corlett, "RULA: a survey method for the investigation of work-related upper limb disorders," *Appl. Ergon.*, vol. 24, no. 2, pp. 91–99, Apr. 1993, doi: 10.1016/0003-6870(93)90080-S.

[25] H. Wang, J. Hwang, K.-S. Lee, J.-S. Kwag, J.-S. Jang, and M.-C. Jung, "Upper Body and Finger Posture Evaluations at an Electric Iron Assembly Plant," *Hum. Factors Ergon. Manuf. Serv. Ind.*, vol. 24, no. 2, pp. 161–171, Mar. 2014, doi: 10.1002/hfm.20362.

[26] K. S. Lee and M. C. Jung, "Investigation of hand postures in manufacturing industries according to hand and object properties," *Int. J. Ind. Ergon.*, vol. 46, pp. 98–104, 2015, doi: 10.1016/j.ergon.2015.01.001.

[27] T. Feix, J. Romero, H. B. Schmiedmayer, A. M. Dollar, and D. Kragic, "The GRASP Taxonomy of Human Grasp Types," *IEEE Trans. Human-Machine Syst.*, vol. 46, no. 1, pp. 66–77, 2016, doi: 10.1109/THMS.2015.2470657.

[28] S. J. Edwards, D. J. Buckland, and J. D. Mccoy-Powlen, *Developmental Functional Hand Grasps*, 1st ed. Thorofare, NJ: Slack Inc, 2002.

[29] M. Cutkosky and P. Wright, "Modeling manufacturing grips and correlations with the design of robotic hands," in *Proceedings. 1986 IEEE International Conference on Robotics and Automation*, vol. 3, pp. 1533–1539, doi: 10.1109/ROBOT.1986.1087525.

[30] H. M. Schambra, A. Parnandi, N. J. Pandit, J. Uddin, A. Wirtanen, and D. M. Nilsen, "A taxonomy of functional upper extremity motion," *Front. Neurol.*, vol. 10, no. JUL, 2019, doi: 10.3389/fneur.2019.00857.

[31] K. Wolf, A. Naumann, M. Rohs, and J. Müller, "A taxonomy of microinteractions: Defining microgestures based on ergonomic and scenario-Dependent requirements," *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 6946 LNCS, no. PART 1, pp. 559–575, 2011, doi: 10.1007/978-3-642-23774-4_45.

[32] R. Safaee-Rad, E. Shwedyk, A. O. Quanbury, and J. E. Cooper, "Normal Functional Range of Motion of Upper Limb Joints During Performance

of Three Feeding Activities," *Arch Phys Med Rehabil*, vol. 71, no. 7, pp. 505–509, 1990.

[33] C. Ansuini, A. Cavallo, A. Koul, M. Jacono, Y. Yang, and C. Becchio, "Predicting object size from hand kinematics: A temporal perspective," *PLoS One*, vol. 10, no. 3, pp. 1–13, 2015, doi: 10.1371/journal.pone.0120432.

[34] M. F. Sani, M. Esteban Ochoa, and S. Dogramadzi, "Palm reading: Using palm deformation for fingers and thumb pose estimation," *IEEE Int. Conf. Robot. Biomimetics, ROBIO 2019*, no. December, pp. 2964–2970, 2019, doi: 10.1109/ROBIO49542.2019.8961467.

[35] H. A. Rahman, Y. C. Fai, and E. S. L. Ming, "Evaluation of hand kinematics in upward reaching movement," *J. Med. Imaging Heal. Informatics*, vol. 3, no. 4, pp. 551–554, 2013, doi: 10.1166/jmihi.2013.1203.

[36] F. Stival, S. Michieletto, M. Cognolato, E. Pagello, H. Müller, and M. Atzori, "A quantitative taxonomy of human hand grasps," *J. Neuroeng. Rehabil.*, vol. 16, no. 1, pp. 1–17, 2019, doi: 10.1186/s12984-019-0488-x.

[37] A. Roda-Sales, M. Vergara, J. L. Sancho-Bru, V. Gracia-Ibáñez, and N. J. Jarque-Bou, "Effect on hand kinematics when using assistive devices during activities of daily living," *PeerJ*, vol. 7, p. e7806, 2019, doi: 10.7717/peerj.7806.

[38] I. Albuquerque Mesquita *et al.*, "Comparison of upper limb kinematics in two activities of daily living with different handling requirements," *Hum. Mov. Sci.*, vol. 72, no. May, p. 102632, 2020, doi: 10.1016/j.humov.2020.102632.

[39] J. N. Ingram, K. P. Körding, I. S. Howard, and D. M. Wolpert, "The statistics of natural hand movements," *Exp. Brain Res.*, vol. 188, no. 2, pp. 223–236, Jun. 2008, doi: 10.1007/s00221-008-1355-3.

[40] H. A. Rahman, K. X. Khor, C. F. Yeong, E. L. M. Su, and A. L. T. Narayanan, "The potential of iRest in measuring the hand function performance of stroke patients," *Biomed. Mater. Eng.*, vol. 28, no. 2, pp. 105–116, 2017, doi: 10.3233/BME-171660.

[41] M. Jeannerod, *The neural and behavioural organization of goal-directed movements*. Oxford: Oxford University Press, 1988.

[42] E. Kholinne *et al.*, "The Dimensionless Squared Jerk: An Objective Parameter That Improves Assessment of Hand Motion Analysis during Simulated Shoulder Arthroscopy," *Biomed Res. Int.*, vol. 2018, 2018, doi: 10.1155/2018/7816160.

[43] A. Kritikos, J. Dunai, and U. Castiello, "Modulation of reach-to-grasp parameters: Semantic category, volumetric properties and distractor

interference?," *Exp. Brain Res.*, vol. 138, no. 1, pp. 54–61, 2001, doi: 10.1007/s002210000641.

[44] N. A. Baker, R. Cham, E. H. Cidboy, J. Cook, and M. S. Redfern, "Kinematics of the fingers and hands during computer keyboard use," *Clin. Biomech.*, vol. 22, no. 1, pp. 34–43, 2007, doi: 10.1016/j.clinbiomech.2006.08.008.

[45] A. M. Valevicius *et al.*, "Characterization of normative hand movements during two functional upper limb tasks," *PLoS One*, vol. 13, no. 6, pp. 1–21, 2018, doi: 10.1371/journal.pone.0199549.

[46] A. Kritikos, M. Beresford, and U. Castiello, "Tactile interference in visually guided reach-to-grasp movements," *Exp. Brain Res.*, vol. 144, no. 1, pp. 1–7, 2002, doi: 10.1007/s00221-002-1004-1.

[47] M. A. Murphy, C. Willén, and K. S. Sunnerhagen, "Kinematic variables quantifying upper-extremity performance after stroke during reaching and drinking from a glass," *Neurorehabil. Neural Repair*, vol. 25, no. 1, pp. 71–80, 2011, doi: 10.1177/1545968310370748.

[48] A. Merlo *et al.*, "Upper limb evaluation with robotic exoskeleton. Normative values for indices of accuracy, speed and smoothness," *NeuroRehabilitation*, vol. 33, no. 4, pp. 523–530, 2013, doi: 10.3233/NRE-130998.

[49] E. E. Butler, A. L. Ladd, L. E. LaMont, and J. Rose, "Temporal-spatial parameters of the upper limb during a Reach & Grasp Cycle for children," *Gait Posture*, vol. 32, no. 3, pp. 301–306, 2010, doi: 10.1016/j.gaitpost.2010.05.013.

[50] P. S. Lum, S. Mulroy, R. L. Amdur, P. Requejo, B. I. Prilutsky, and A. W. Dromerick, "Gains in upper extremity function after stroke via recovery or compensation: Potential differential effects on amount of real-world limb use," *Top. Stroke Rehabil.*, vol. 16, no. 4, pp. 237–253, 2009, doi: 10.1310/tsr1604-237.

[51] B. Rohrer *et al.*, "Movement smoothness changes during stroke recovery," *J. Neurosci.*, vol. 22, no. 18, pp. 8297–8304, 2002, doi: 10.1523/jneurosci.22-18-08297.2002.

[52] J. Zariffa *et al.*, "Relationship between clinical assessments of function and measurements from an upper-limb robotic rehabilitation device in cervical spinal cord injury," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 20, no. 3, pp. 341–350, 2012, doi: 10.1109/TNSRE.2011.2181537.

[53] S. Balasubramanian, A. Melendez-Calderon, and E. Burdet, "A robust and sensitive metric for quantifying movement smoothness," *IEEE Trans. Biomed. Eng.*, vol. 59, no. 8, pp. 2126–2136, 2012, doi: 10.1109/TBME.2011.2179545.

[54] S. Balasubramanian, A. Melendez-Calderon, A. Roby-Brami, and E. Burdet, “On the analysis of movement smoothness,” *J. Neuroeng. Rehabil.*, vol. 12, no. 1, pp. 1–11, 2015, doi: 10.1186/s12984-015-0090-9.

[55] V. Gracia-Ibáñez, J. L. Sancho-Bru, M. Vergara, N. J. Jarque-Bou, and A. Roda-Sales, “Sharing of hand kinematic synergies across subjects in daily living activities,” *Sci. Rep.*, vol. 10, no. 1, pp. 1–11, 2020, doi: 10.1038/s41598-020-63092-7.

[56] M. Santello *et al.*, “Hand synergies: Integration of robotics and neuroscience for understanding the control of biological and artificial hands,” *Phys. Life Rev.*, vol. 17, pp. 1–23, 2016, doi: 10.1016/j.plrev.2016.02.001.

[57] N. J. Jarque-Bou, M. Vergara, J. L. Sancho-Bru, V. Gracia-Ibanez, and A. Roda-Sales, “Hand Kinematics Characterization while Performing Activities of Daily Living through Kinematics Reduction,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 28, no. 7, pp. 1556–1565, 2020, doi: 10.1109/TNSRE.2020.2998642.

[58] P. M. Fitts, “The information capacity of the human motor system in controlling the amplitude of movement,” *J. Exp. Psychol.*, vol. 47, no. 6, pp. 381–391, 1954.

[59] O. Celik, M. K. O’Malley, C. Boake, H. S. Levin, N. Yozbatiran, and T. A. Reistetter, “Normalized movement quality measures for therapeutic robots strongly correlate with clinical motor impairment measures,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 18, no. 4, pp. 433–444, 2010, doi: 10.1109/TNSRE.2010.2047600.

[60] C. E. Lang *et al.*, “Deficits in grasp versus reach during acute hemiparesis,” *Exp. Brain Res.*, vol. 166, no. 1, pp. 126–136, 2005, doi: 10.1007/s00221-005-2350-6.

[61] Y. C. Hung, J. Charles, and A. M. Gordon, “Bimanual coordination during a goal-directed task in children with hemiplegic cerebral palsy,” *Dev. Med. Child Neurol.*, vol. 46, no. 11, pp. 746–753, 2004, doi: 10.1017/S0012162204001288.

[62] B. Steenbergen, W. Hulstijn, A. De Vries, and M. Berger, “Bimanual movement coordination in spastic hemiparesis,” *Exp. Brain Res.*, vol. 110, no. 1, pp. 91–98, 1996, doi: 10.1007/BF00241378.

[63] J. Rudisch *et al.*, “Kinematic parameters of hand movement during a disparate bimanual movement task in children with unilateral Cerebral Palsy,” *Hum. Mov. Sci.*, vol. 46, pp. 239–250, 2016, doi: 10.1016/j.humov.2016.01.010.

[64] G. L. Fellows and A. Freivalds, “Ergonomics evaluation of a foam rubber grip for tool handles,” *Appl. Ergon.*, vol. 22, no. 4, pp. 225–230, 1991, doi: 10.1016/0003-6870(91)90225-7.

[65] C. Fransson-Hall and Å. Kilbom, "Sensitivity of the hand to surface pressure," *Appl. Ergon.*, vol. 24, no. 3, pp. 181–189, 1993, doi: 10.1016/0003-6870(93)90006-U.

[66] V. Mathiowetz, N. Kashman, G. Volland, K. Weber, M. Dowe, and S. Rogers, "Grip and Pinch Strength: Normative Data for Adults," *Arch Phys Med Rehabil*, vol. 66, no. 2, pp. 69–74, 1985.

[67] L. Peebles and B. Norris, "Filling 'gaps' in strength data for design," *Appl. Ergon.*, vol. 34, no. 1, pp. 73–88, 2003, doi: 10.1016/S0003-6870(02)00073-X.

[68] J. R. Flanagan and A. M. Wing, "The stability of precision grip forces during cyclic arm movements with a hand-held load," *Exp. Brain Res.*, vol. 105, no. 3, pp. 455–464, 1990, doi: 10.1007/BF00233045.

[69] J. Rowson and A. Yoxall, "Hold, grasp, clutch or grab: Consumer grip choices during food container opening," *Appl. Ergon.*, vol. 42, no. 5, pp. 627–633, 2011, doi: 10.1016/j.apergo.2010.12.001.

[70] M. Santello and J. F. Soechting, "Force synergies for multifingered grasping," *Exp. Brain Res.*, vol. 133, no. 4, pp. 457–467, Aug. 2000, doi: 10.1007/s002210000420.

[71] R. G. Radwin, T. J. Armstrong, and D. B. Chaffin, "Power hand tool vibration effects on grip exertions," *Ergonomics*, vol. 30, no. 5, pp. 833–855, 1987, doi: 10.1080/00140138708969772.

[72] N. J. Jarque-Bou, M. Vergara, J. L. Sancho-Bru, V. Gracia-Ibáñez, and A. Roda-Sales, "A calibrated database of kinematics and EMG of the forearm and hand during activities of daily living," *Sci. data*, vol. 6, no. 1, p. 270, 2019, doi: 10.1038/s41597-019-0285-1.

[73] M. Cognolato *et al.*, "Gaze, visual, myoelectric, and inertial data of grasps for intelligent prosthetics," *Sci. Data*, vol. 7, no. 1, pp. 1–15, 2020, doi: 10.1038/s41597-020-0380-3.

[74] G. A. V. BORG, "Psychophysical bases of perceived exertion," *Med. Sci. Sport. Exerc.*, vol. 14, no. 5, pp. 377–381, May 1982, doi: 10.1249/00005768-198205000-00012.

[75] C. B. Irwin, J. D. Towles, and R. G. Radwin, "Multiaxis grip characteristics for varying handle diameters and effort," *Hum. Factors*, vol. 57, no. 2, pp. 227–237, 2015, doi: 10.1177/0018720814544212.

[76] A. Yoxall, V. Gonzalez, J. Best, E. M. Rodriguez-Falcon, and J. Rowson, "As you like it: Understanding the relationship between packing design and accessibility," *Packag. Technol. Sci.*, vol. 32, no. 10, pp. 496–507, 2019, doi: 10.1002/pts.2466.

[77] S. V. Duff, D. H. Aaron, G. R. Gogola, and F. J. Valero-Cuevas, "Innovative evaluation of dexterity in pediatrics," *J. Hand Ther.*, vol.

28, no. 2, pp. 144–150, 2015, doi: 10.1016/j.jht.2015.01.004.

[78] J. Gielen, J. Laton, J. Van Schependom, P. P. De Deyn, and G. Nagels, "The squares test as a measure of hand function in multiple sclerosis," *Clin. Neurol. Neurosurg.*, vol. 123, pp. 55–60, 2014, doi: 10.1016/j.clineuro.2014.05.008.

[79] N. Taylor, P. L. Sand, and R. H. Jebsen, "Evaluation of hand function in children.," *Arch. Phys. Med. Rehabil.*, vol. 54, no. 3, pp. 129–35, Mar. 1973, [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/4696054.

[80] V. Mathiowetz, G. Volland, N. Kashman, and K. Weber, "Adult Norms for the Box and Block Test of Manual Dexterity," *Am. J. Occup. Ther.*, vol. 39, no. 6, pp. 386–391, Jun. 1985, doi: 10.5014/ajot.39.6.386.

[81] J. Tiffin and E. J. Asher, "The Purdue Pegboard: norms and studies of reliability and validity.," *J. Appl. Psychol.*, vol. 32, no. 3, pp. 234–247, 1948, doi: 10.1037/h0061266.

[82] C. Sollerman and A. Ejeskär, "Sollerman Hand Function Test: A Standardised Method and its Use in Tetraplegic Patients," *Scand. J. Plast. Reconstr. Surg. Hand Surg.*, vol. 29, no. 2, pp. 167–176, Jan. 1995, doi: 10.3109/02844319509034334.

[83] Y.-C. Wang, R. Wickstrom, S.-C. Yen, J. Kapellusch, and K. A. Grogan, "Assessing manual dexterity: Comparing the WorkAbility Rate of Manipulation Test with the Minnesota Manual Dexterity Test," *J. Hand Ther.*, vol. 31, no. 3, pp. 339–347, Jul. 2018, doi: 10.1016/j.jht.2017.03.009.

[84] Y.-C. Wang, R. Wickstrom, S.-C. Yen, J. Kapellusch, and K. A. Grogan, "Assessing manual dexterity: Comparing the WorkAbility Rate of Manipulation Test with the Minnesota Manual Dexterity Test," *J. Hand Ther.*, vol. 31, no. 3, pp. 339–347, Jul. 2018, doi: 10.1016/j.jht.2017.03.009.

[85] C. Gagnon *et al.*, "Validity and Reliability of Outcome Measures Assessing Dexterity, Coordination, and Upper Limb Strength in Autosomal Recessive Spastic Ataxia of Charlevoix-Saguenay," *Arch. Phys. Med. Rehabil.*, vol. 99, no. 9, pp. 1747–1754, Sep. 2018, doi: 10.1016/j.apmr.2018.01.026.

[86] M. L. Baumann, J. M. Cancio, and K. E. Yancosek, "The suitcase packing activity: A new evaluation of hand function," *J. Hand Ther.*, vol. 30, no. 3, pp. 359–366, Jul. 2017, doi: 10.1016/j.jht.2017.02.002.

[87] H. Arwert, S. Schut, J. Boiten, T. Vliet Vlieland, and J. Meesters, "Patient reported outcomes of hand function three years after stroke," *Top. Stroke Rehabil.*, vol. 25, no. 1, pp. 13–19, Jan. 2018, doi: 10.1080/10749357.2017.1385232.

[88] S.-Y. Lin, J.-K. Chang, P.-C. Chen, and H.-F. Mao, "Hand function measures for burn patients: A literature review," *Burns*, vol. 39, no. 1, pp. 16–23, Feb. 2013, doi: 10.1016/j.burns.2012.08.020.

[89] S.-Y. Lin, J.-K. Chang, P.-C. Chen, and H.-F. Mao, "Hand function measures for burn patients: A literature review," *Burns*, vol. 39, no. 1, pp. 16–23, Feb. 2013, doi: 10.1016/j.burns.2012.08.020.

[90] A. Hoang-Kim, F. Pegreffi, A. Moroni, and A. Ladd, "Measuring wrist and hand function: Common scales and checklists," *Injury*, vol. 42, no. 3, pp. 253–258, Mar. 2011, doi: 10.1016/j.injury.2010.11.050.

[91] A. Hoang-Kim, F. Pegreffi, A. Moroni, and A. Ladd, "Measuring wrist and hand function: Common scales and checklists," *Injury*, vol. 42, no. 3, pp. 253–258, Mar. 2011, doi: 10.1016/j.injury.2010.11.050.

[92] N. Naughton and L. Algar, "Linking commonly used hand therapy outcome measures to individual areas of the International Classification of Functioning: A systematic review," *J. Hand Ther.*, vol. 32, no. 2, pp. 243–261, Apr. 2019, doi: 10.1016/j.jht.2017.11.039.

[93] N. Naughton and L. Algar, "Linking commonly used hand therapy outcome measures to individual areas of the International Classification of Functioning: A systematic review," *J. Hand Ther.*, vol. 32, no. 2, pp. 243–261, Apr. 2019, doi: 10.1016/j.jht.2017.11.039.

[94] M. H. Hoonhorst, R. H. Nijland, J. S. van den Berg, C. H. Emmelot, B. J. Kollen, and G. Kwakkel, "How Do Fugl-Meyer Arm Motor Scores Relate to Dexterity According to the Action Research Arm Test at 6 Months Poststroke?," *Arch. Phys. Med. Rehabil.*, vol. 96, no. 10, pp. 1845–1849, Oct. 2015, doi: 10.1016/j.apmr.2015.06.009.

[95] M. K. Y. Mak, E. T. L. Lau, V. W. K. Tam, C. W. Y. Woo, and S. K. Y. Yuen, "Use of Jebsen Taylor Hand Function Test in evaluating the hand dexterity in people with Parkinson's disease," *J. Hand Ther.*, vol. 28, no. 4, pp. 389–395, Oct. 2015, doi: 10.1016/j.jht.2015.05.002.

[96] Y.-C. Wang *et al.*, "Assessing Dexterity Function: A Comparison of Two Alternatives for the NIH Toolbox," *J. Hand Ther.*, vol. 24, no. 4, pp. 313–321, Oct. 2011, doi: 10.1016/j.jht.2011.05.001.

[97] L. Krumlinde-Sundholm, B. Lindkvist, J. Plantin, and B. Hoare, "Development of the assisting hand assessment for adults following stroke: a Rasch-built bimanual performance measure," *Disabil. Rehabil.*, vol. 41, no. 4, pp. 472–480, Feb. 2019, doi: 10.1080/09638288.2017.1396365.

[98] D. Johnson, J. Harris, P. Stratford, and J. Richardson, "Inter-rater reliability of the Chedoke Arm and Hand Activity Inventory," *NeuroRehabilitation*, vol. 40, no. 2, pp. 201–209, Mar. 2017, doi: 10.3233/NRE-161405.

[99] N. J. Jarque-Bou, M. Atzori, and H. Müller, “A large calibrated database of hand movements and grasps kinematics,” *Sci. Data*, vol. 7, no. 1, pp. 1–10, 2020, doi: 10.1038/s41597-019-0349-2.

[100] M. Atzori *et al.*, “Electromyography data for non-invasive naturally-controlled robotic hand prostheses,” *Sci. Data*, vol. 1, pp. 1–13, 2014, doi: 10.1038/sdata.2014.53.

[101] N. J. Jarque-Bou, A. Scano, M. Atzori, and H. Müller, “Kinematic synergies of hand grasps: A comprehensive study on a large publicly available dataset,” *J. Neuroeng. Rehabil.*, vol. 16, no. 1, pp. 1–14, 2019, doi: 10.1186/s12984-019-0536-6.

[102] S. Sundaram, P. Kellnhofer, Y. Li, J. Y. Zhu, A. Torralba, and W. Matusik, “Learning the signatures of the human grasp using a scalable tactile glove,” *Nature*, vol. 569, no. 7758, pp. 698–702, 2019, doi: 10.1038/s41586-019-1234-z.

[103] K. Katsiaris, P., Artemiadis, P., & Kyriakopoulos, “Hand Corpus.” 2010, doi: http://www.handcorpus.org/?p=100.

[104] A. Bianchi, M., Salaris, P. & Bicchi, “Hand Corpus.” 2011, doi: http://www.handcorpus.org/?p=103.

[105] M. Bianchi, P. Salaris, and A. Bicchi, “Synergy-based hand pose sensing: Reconstruction enhancement,” *Int. J. Rob. Res.*, vol. 32, no. 4, pp. 396–406, 2013, doi: 10.1177/0278364912474078.

[106] M. Santello, M. Flanders, and J. F. Soechting, “Postural hand synergies for tool use,” *J. Neurosci.*, vol. 18, no. 23, pp. 10105–10115, 1998.

[107] J. F. Santello, M., Flanders, M. & Soechting, “Hand Corpus.” 2011, doi: http://www.handcorpus.org/?p=91.

[108] J. F. Santello, M., Flanders, M. & Soechting, “Hand Corpus.” 2012, doi: http://www.handcorpus.org/?p=97.

[109] G. Stillfried, “Kinematic modelling of the human hand for robotics,” *PhD Thesis*, 2015.

[110] G. Stillfried, “Hand Corpus.” 2013, doi: http://www.handcorpus.org/?p=1109.

[111] M. Gabiccini, G. Stillfried, H. Marino, and M. Bianchi, “A data-driven kinematic model of the human hand with soft-tissue artifact compensation mechanism for grasp synergy analysis,” *IEEE Int. Conf. Intell. Robot. Syst.*, no. 0, pp. 3738–3745, 2013, doi: 10.1109/IROS.2013.6696890.

[112] M. Gabiccini, M., Stillfried, G., Marino, H. & Bianchi, “Hand Corpus.” 2013, doi: http://www.handcorpus.org/?p=1156.

[113] M. Gabiccini, M., Stillfried, G., Marino, H. & Bianchi, "Hand Corpus." 2014, doi: http://www.handcorpus.org/?p=1298.

[114] M. Gabiccini, M., Stillfried, G., Marino, H. & Bianchi, "Hand Corpus." 2014, doi: http://www.handcorpus.org/?p=1354.

[115] R. Deimel and O. Brock, "A novel type of compliant and underactuated robotic hand for dexterous grasping," *Int. J. Rob. Res.*, vol. 35, no. 1–3, pp. 161–185, 2016, doi: 10.1177/0278364915592961.

[116] O. Deimel, R. & Brock, "Hand Corpus." 2015, doi: http://www.handcorpus.org/?p=1507.

[117] M. Gabiccini, M., Stillfried, G., Marino, H. & Bianchi, "Hand Corpus." 2015, doi: http://www.handcorpus.org/?p=1578.

[118] M. J. Liu, C. H. Xiong, L. Xiong, and X. L. Huang, "Biomechanical characteristics of hand coordination in grasping activities of daily living," *PLoS One*, vol. 11, no. 1, pp. 1–16, 2016, doi: 10.1371/journal.pone.0146193.

[119] X. L. Liu, M. J., Xiong, C. H., Xiong, L. & Huang, "Hand Corpus." 2016, doi: http://www.handcorpus.org/?p=1596.

[120] M. Puhlmann, Steffen and Heinemann, Fabian and Brock, Oliver and Maertens, "A Compact Representation of Human Single-Object Grasping," in *2016 IEEE International Conference on Intelligent Robots and Systems (IROS)*, 2016, pp. 1954–1959.

[121] M. Puhlmann, S., Heinemann, F., Brock, O. & Maertens, "Hand Corpus." 2016, doi: http://www.handcorpus.org/?p=1830.

[122] C. Della Santina *et al.*, "Postural hand synergies during environmental constraint exploitation," *Front. Neurorobot.*, vol. 11, no. August, pp. 1–14, 2017, doi: 10.3389/fnbot.2017.00041.

[123] A. Della Santina, C., Bianchi, C. M., Averta, G., Ciotti, S., Arapi, V., Fani, S., Battaglia, E., Catalano, M.G., Santello, M., & Bicchi, "Hand Corpus." 2018, doi: http://www.handcorpus.org/?p=1855.

[124] H. Atzori, M., Gijsberts, A., Castellini, C., Caputo, B., Mittaz Hage, A.G., Elsig, S., Giatsidis, G., Bassetto, F. & Müller, "Ninaweb." 2014, doi: http://ninapro.hevs.ch/.

[125] B. Calli, A. Wallsman, A. Singfh, and S. S. Srinivasa, "Benchmarking in Manipulation Research," *IEEE Robot. Autom. Mag.*, no. September, pp. 36–52, 2015, doi: 10.1109/MRA.2015.2448951.

[126] D. Eastough and M. G. Edwards, "Movement kinematics in prehension are affected by grasping objects of different mass," *Exp. Brain Res.*, vol. 176, no. 1, pp. 193–198, 2007, doi: 10.1007/s00221-006-0749-3.

[127] V. Gracia-Ibáñeez, J. L. Sancho-Bru, and M. Vergara, "Relevance of grasp types to assess functionality for personal autonomy," *J. Hand Ther.*, 2016, doi: 10.1016/j.jht.2017.02.003.

[128] T. Feix, I. M. Bullock, and A. M. Dollar, "Analysis of human grasping behavior: Correlating tasks, objects and grasps," *IEEE Trans. Haptics*, vol. 7, no. 4, pp. 430–441, 2014, doi: 10.1109/TOH.2014.2326867.

[129] J. Hwang, Y.-K. Kong, and M.-C. Jung, "Posture evaluations of tethering and loose-housing systems in dairy farms," *Appl. Ergon.*, vol. 42, no. 1, pp. 1–8, Dec. 2010, doi: 10.1016/j.apergo.2010.03.008.

[130] T. Feix, I. M. Bullock, and A. M. Dollar, "Analysis of human grasping behavior: Object characteristics and grasp type," *IEEE Trans. Haptics*, vol. 7, no. 3, pp. 311–323, 2014, doi: 10.1109/TOH.2014.2326871.

[131] I. M. Bullock, T. Feix, and A. M. Dollar, "The Yale human grasping dataset: Grasp, object, and task data in household and machine shop environments," *Int. J. Rob. Res.*, vol. 34, no. 3, pp. 251–255, 2015, doi: 10.1177/0278364914555720.

[132] I. M. Bullock, T. Feix, and A. M. Dollar, "The Yale Human Grasping Data Set: Grasp, Object and Task Data in Household and Machine Shop Environments," *Online*, 2014. http://www.eng.yale.edu/grablab/humangrasping/ (accessed Oct. 27, 2020).

[133] J. D. Morrow and P. K. Khosla, "Manipulation task primitives for composing robot skills," in *Proceedings of International Conference on Robotics and Automation*, 1997, vol. 4, pp. 3354–3359, doi: 10.1109/ROBOT.1997.606800.

[134] X. Chen, Z. Li, and Y. Wang, "Effect of object and human-factor characteristics on the preference of thumb-index finger grasp type," *Ergonomics*, vol. 0, no. 0, pp. 1–14, 2020, doi: 10.1080/00140139.2020.1782997.

[135] K. S. Lee and M. C. Jung, "Common patterns of voluntary grasp types according to object shape, size, and direction," *Int. J. Ind. Ergon.*, vol. 44, no. 5, pp. 761–768, 2014, doi: 10.1016/j.ergon.2014.08.005.

[136] C. Ansuini, M. Santello, S. Massaccesi, and U. Castiello, "Effects of end-goal on hand shaping," *J. Neurophysiol.*, vol. 95, no. 4, pp. 2456–2465, 2006, doi: 10.1152/jn.01107.2005.

[137] G. I. Bain, N. Polites, B. G. Higgs, R. J. Heptinstall, and A. M. McGrath, "The functional range of motion of the finger joints," *J. Hand Surg. Eur. Vol.*, vol. 40, no. 4, pp. 406–411, 2015, doi: 10.1177/1753193414533754.

[138] R. . Hume, M.C; Gellman, H.; McKellop, H., Brumfield, "Functional Motion of the joints of the hand," *Am. Acad. Orthop. Surg.*, pp. 240–243,

1999.

[139] T. Murai, S. Uchiyama, K. Nakamura, Y. Ido, Y. Hata, and H. Kato, "Functional range of motion in the metacarpophalangeal joints of the hand measured by single axis electric goniometers," *J. Orthop. Sci.*, vol. 23, no. 3, pp. 504–510, 2018, doi: 10.1016/j.jos.2018.01.013.

[140] N. M. Hadler *et al.*, "Hand structure and function in an industrial setting.," *Arthritis Rheum.*, vol. 21, no. 2, pp. 210–220, 1978, doi: 10.1002/art.1780210206.

[141] T. Bazański, "Metacarpophalangeal joint kinematics during a grip of everyday objects using the three-dimensional motion analysis system," *Acta Bioeng. Biomech.*, vol. 12, no. 2, pp. 79–85, 2010.

[142] L. H. Wang, L. C. Kuo, S. W. Shih, K. C. Lo, and F. C. Su, "Comparison of dominant hand range of motion among throwing types in baseball pitchers," *Hum. Mov. Sci.*, vol. 32, no. 4, pp. 719–729, 2013, doi: 10.1016/j.humov.2013.01.003.

[143] C. Ansuini, L. Giosa, L. Turella, G. Altoè, and U. Castiello, "An object for an action, the same object for other actions: Effects on hand shaping," *Exp. Brain Res.*, vol. 185, no. 1, pp. 111–119, 2008, doi: 10.1007/s00221-007-1136-4.

[144] S. S. McDonald, D. Levine, J. Richards, and L. Aguilar, "Effectiveness of adaptive silverware on range of motion of the hand," *PeerJ*, vol. 4, p. e1667, Feb. 2016, doi: 10.7717/peerj.1667.

[145] A. A. Amis, "Variation of finger forces in maximal isometric grasp tests on a range of cylinder diameters," *J. Biomed. Eng.*, vol. 9, no. 4, pp. 313–320, 1987, doi: 10.1016/0141-5425(87)90079-3.

[146] H.-I. Ma, W.-J. Hwang, P.-L. Tsai, and Y.-W. Hsu, "The effect of eating utensil weight on functional arm movement in people with Parkinson's disease: a controlled clinical trial," *Clin. Rehabil.*, vol. 23, no. 12, pp. 1086–1092, Dec. 2009, doi: 10.1177/0269215509342334.

[147] H.-I. Ma, W.-J. Hwang, M.-J. Chen-Sea, and C.-F. Sheu, "Handle size as a task constraint in spoon-use movement in patients with Parkinson's disease.," *Clin. Rehabil.*, vol. 22, no. 6, pp. 520–528, 2008, doi: 10.1177/0269215507086181.

[148] D. Van and B. Steenbergen, "The use of ergonomic spoons by people with cerebral palsy: effects on food spilling and movement kinematics," *Dev. Med. Child Neurol.*, vol. 48, no. 11, pp. 888–891, Feb. 2007, doi: 10.1111/j.1469-8749.2006.01940a.x.

[149] C. E. Lang, J. M. Wagner, D. F. Edwards, S. A. Sahrmann, and A. W. Dromerick, "Recovery of Grasp versus Reach in People with Hemiparesis Poststroke," *Neurorehabil. Neural Repair*, vol. 20, no. 4,

pp. 444–454, Dec. 2006, doi: 10.1177/1545968306289299.

[150] T. Flash and N. Hogan, "The coordination of arm movements: An experimentally confirmed mathematical model," *J. Neurosci.*, vol. 5, no. 7, pp. 1688–1703, 1985, doi: 10.1523/jneurosci.05-07-01688.1985.

[151] B. Poston, A. W. A. Van Gemmert, S. Sharma, S. Chakrabarti, S. H. Zavaremi, and G. Stelmach, "Movement trajectory smoothness is not associated with the endpoint accuracy of rapid multi-joint arm movements in young and older adults," *Acta Psychol. (Amst).*, vol. 143, no. 2, pp. 157–167, 2013, doi: 10.1016/j.actpsy.2013.02.011.

[152] Q. C. Pham, H. Hicheur, G. Arechavaleta, J. P. Laumond, and A. Berthoz, "The formation of trajectories during goal-oriented locomotion in humans. II. A maximum smoothness model," *Eur. J. Neurosci.*, vol. 26, no. 8, pp. 2391–2403, 2007, doi: 10.1111/j.1460-9568.2007.05835.x.

[153] H. I. Krebs, M. L. Aisen, B. T. Volpe, and N. Hogan, "Quantization of continuous arm movements in humans with brain injury," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 96, no. 8, pp. 4645–4649, 1999, doi: 10.1073/pnas.96.8.4645.

[154] A. Yoxall, V. Gonzalez, and J. Rowson, "Analysis of Finger Motion Coordination during Packaging Interactions," *Packag. Technol. Sci.*, vol. 31, no. 6, pp. 389–400, Jun. 2018, doi: 10.1002/pts.2319.

[155] K. J. Cole and J. H. Abbs, "Coordination of three-joint digit movements for rapid finger-thumb grasp," *J. Neurophysiol.*, vol. 55, no. 6, pp. 1407–1423, Jun. 1986, doi: 10.1152/jn.1986.55.6.1407.

[156] W. G. Darling, K. J. Cole, and J. H. Abbs, "Kinematic variability of grasp movements as a function of practice and movement speed," *Exp. Brain Res.*, vol. 73, no. 2, pp. 1407–1423, Nov. 1988, doi: 10.1007/BF00248215.

[157] M. J. Schreck *et al.*, "Dynamic Functional Assessment of Hand Motion Using an Animation Glove: The Effect of Stenosing Tenosynovitis," *Hand*, vol. 13, no. 6, pp. 695–704, 2018, doi: 10.1177/1558944717729218.

[158] R. Vinjamuri, Z. H. Mao, R. Sclabassi, and M. Sun, "Time-varying synergies in velocity profiles of finger joints of the hand during reach and grasp," *Annu. Int. Conf. IEEE Eng. Med. Biol. - Proc.*, pp. 4846–4849, 2007, doi: 10.1109/IEMBS.2007.4353425.

[159] I. V Grinyagin, E. V Biryukova, and M. A. Maier, "Kinematic and dynamic synergies of human precision-grip movements.," *J. Neurophysiol.*, vol. 94, pp. 2284–2294, 2005, doi: 10.1152/jn.01310.2004.

[160] R. Vinjamuri, M. Sun, C. C. Chang, H. N. Lee, R. J. Sclabassi, and Z. H. Mao, "Temporal postural synergies of the hand in rapid grasping tasks," *IEEE Trans. Inf. Technol. Biomed.*, vol. 14, no. 4, pp. 986–994, 2010,

doi: 10.1109/TITB.2009.2038907.

[161] M. Santello, G. Baud-Bovy, and H. Jörntell, “Neural bases of hand synergies,” *Front. Comput. Neurosci.*, vol. 7, no. MAR, pp. 1–15, 2013, doi: 10.3389/fncom.2013.00023.

[162] C. E. Lang and M. H. Schieber, “Human finger independence: Limitations due to passive mechanical coupling versus active neuromuscular control,” *J. Neurophysiol.*, vol. 92, no. 5, pp. 2802–2810, 2004, doi: 10.1152/jn.00480.2004.

[163] N. Jarque-Bou, V. Gracia-Ibáñez, J. L. Sancho-Bru, M. Vergara, A. Pérez-González, and F. J. Andrés, “Using kinematic reduction for studying grasping postures. An application to power and precision grasp of cylinders,” *Appl. Ergon.*, vol. 56, pp. 52–61, 2016, doi: 10.1016/j.apergo.2016.03.003.

[164] A. M. Valevicius, P. Y. Jun, J. S. Hebert, and A. H. Vette, “Use of optical motion capture for the analysis of normative upper body kinematics during functional upper limb tasks: A systematic review,” *J. Electromyogr. Kinesiol.*, vol. 40, no. February, pp. 1–15, 2018, doi: 10.1016/j.jelekin.2018.02.011.

[165] C. H. Chen, Y. H. Hu, T. Y. Yen, and R. G. Radwin, “Automated video exposure assessment of repetitive hand activity level for a load transfer task,” *Hum. Factors*, vol. 55, no. 2, pp. 298–308, 2013, doi: 10.1177/0018720812458121.

[166] Y. Endo, M. Tada, and M. Mochimaru, “Dhaiba : Development of Virtual Ergonomic Assessment System with Human Models,” in *Digital Human Modeling Synposium*, 2014, no. May, p. #58.

[167] B. León, A. Morales, and J. L. Sancho-Bru, *From Robot to Human Grasping Simulation*, vol. 19. Cham: Springer International Publishing, 2014.

[168] J. L. Sancho-Bru, N. J. Jarque-Bou, M. Vergara, and A. Pérez-González, “Validity of a simple videogrammetric method to measure the movement of all hand segments for clinical purposes,” *Proc. Inst. Mech. Eng. Part H J. Eng. Med.*, vol. 228, no. 2, pp. 182–189, Feb. 2014, doi: 10.1177/0954411914522023.

[169] O. Karhu, P. Kansi, and I. Kuorinka, “Correcting working postures in industry: A practical method for analysis,” *Appl. Ergon.*, vol. 8, no. 4, pp. 199–201, Dec. 1977, doi: 10.1016/0003-6870(77)90164-8.

[170] R. F. Johnson and L. A. Sleeper, “Effects of Chemical Protective Handwear and Headgear on Manual Dexterity,” *Proc. Hum. Factors Soc. Annu. Meet.*, vol. 30, no. 10, pp. 994–997, Sep. 1986, doi: 10.1177/154193128603001011.

[171] A. Muralidhar, R. R. Bishu, and M. S. Hallbeck, "The development and evaluation of an ergonomic glove," *Appl. Ergon.*, vol. 30, no. 6, pp. 555–563, Dec. 1999, doi: 10.1016/S0003-6870(99)00005-8.

[172] R. R. Bishu, G. Klute, and B. Kim, "The Effects of Extra Vehicular Activity (EVA) Gloves on Dexterity and Tactility," *Proc. Hum. Factors Ergon. Soc. Annu. Meet.*, vol. 37, no. 10, pp. 826–830, Oct. 1993, doi: 10.1177/154193129303701038.

[173] I. Dianat, C. M. Haslegrave, and A. W. Stedmon, "Short and longer duration effects of protective gloves on hand performance capabilities and subjective assessments in a screw-driving task," *Ergonomics*, vol. 53, no. 12, pp. 1468–1483, 2010, doi: 10.1080/00140139.2010.528453.

[174] P. Hahn, H. Krimmer, A. Hradetzky, and U. Lanz, "Quantitative Analysis of the Linkage between the interphalangeal Joints of the Index Finger," *J. Hand Surg. Am.*, vol. 20, no. 5, pp. 696–699, Oct. 1995, doi: 10.1016/S0266-7681(05)80139-1.

[175] K. J. Van Zwieten, K. P. Schmidt, G. J. Bex, P. L. Lippens, and W. Duyvendak, "An analytical expression for the D.I.P.-P.I.P. flexion interdependence in human fingers," *Acta Bioeng. Biomech.*, vol. 17, no. 1, pp. 129–135, 2015, doi: 10.5277/ABB-00078-2014-02.

[176] B. H. Kim, "A bio-mimetic inter-articular coordination model for humanoid graspings," *2006 IEEE Conf. Robot. Autom. Mechatronics*, pp. 1–6, 2006, doi: 10.1109/RAMECH.2006.252643.

[177] M. Mentzel, A. Benlic, N. J. Wachter, D. Gulkin, S. Bauknecht, and K. Stuttgart, "Die Dynamik der Bewegungsabl ä ufe der Fingergelenke beim Faustschluss The Dynamics of Motion Sequences of the Finger Joints during Fist Closure," pp. 147–154, 2011.

[178] J. Gülke, N. J. Wachter, T. Geyer, H. Schöll, G. Apic, and M. Mentzel, "Motion Coordination Patterns During Cylinder Grip Analyzed With a Sensor Glove," *J. Hand Surg. Am.*, vol. 35, no. 5, pp. 797–806, 2010, doi: 10.1016/j.jhsa.2009.12.031.

[179] A. Roda-Sales, J. L. Sancho-Bru, M. Vergara, V. Gracia-Ibáñez, and N. J. Jarque-Bou, "Effect on manual skills of wearing instrumented gloves during manipulation," *J. Biomech.*, vol. 98, 2020, doi: 10.1016/j.jbiomech.2019.109512.

[180] V. Gracia-ibáñez, M. Vergara, J. L. Sancho-bru, M. C. Mora, and C. Piqueras, "Functional range of motion of the hand joints in activities of the International Classi fi cation of Functioning , Disability and Health," *J. Hand Ther.*, vol. 30, no. 3, pp. 337–347, 2017, doi: 10.1016/j.jht.2016.08.001.

[181] N. Sarawate, M. C. Leu, and C. Öz, "A real-time American Sign Language word recognition system based on neural networks and a

probabilistic model," *Turkish J. Electr. Eng. Comput. Sci.*, vol. 23, pp. 2107–2123, 2015, doi: 10.3906/elk-1303-167.

[182] B. D. Itkowitz, P. D. Simon, and Z. Tao, "Method and apparatus for hand gesture control in a minimally invasive surgical system," U.S. Patent No. 9,901,402. 27, 2018.

[183] J. D. Lemos, A. M. Hernandez, and G. Soto-Romero, "An instrumented glove to assess manual dexterity in simulation-based neurosurgical education," *Sensors (Switzerland)*, vol. 17, no. 5, 2017, doi: 10.3390/s17050988.

[184] J. L. Sancho-Bru, M. C. Mora, B. E. León, A. Pérez-González, J. L. Iserte, and A. Morales, "Grasp modelling with a biomechanical model of the hand," *Computer Methods in Biomechanics and Biomedical Engineering*, vol. 17, no. 4. Taylor & Francis, pp. 297–310, 2014, doi: 10.1080/10255842.2012.682156.

[185] D. Nogueira, P. Abreu, and M. T. Restivo, "Comparing classification techniques for identification of grasped objects," *Biomed. Eng. Online*, vol. 18, no. 1, pp. 1–14, 2019, doi: 10.1186/s12938-019-0639-0.

[186] A. El-Sawah, N. D. Georganas, and E. M. Petriu, "Calibration and error model analysis of 3D monocular vision model based hand posture estimation," *Conf. Rec. - IEEE Instrum. Meas. Technol. Conf.*, pp. 1–6, 2007.

[187] O. Glauser, S. Wu, D. Panozzo, O. Hilliges, and O. Sorkine-Hornung, "Interactive hand pose estimation using a stretch-sensing soft glove," *ACM Trans. Graph.*, vol. 38, no. 4, pp. 1–15, 2019, doi: 10.1145/3306346.3322957.

[188] N. Jarque-Bou *et al.*, "Exploration of the role of forearm muscles during activities of daily living," *Gait Posture*, vol. 65, pp. 154–155, 2018, doi: 10.1016/j.gaitpost.2018.06.102.

[189] G. R. Naik, A. Acharyya, and H. T. Nguyen, "Classification of finger extension and flexion of EMG and Cyberglove data with modified ICA weight matrix," *2014 36th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBC 2014*, pp. 3829–3832, 2014, doi: 10.1109/EMBC.2014.6944458.

[190] N. Jarrassé, A. T. Ribeiro, A. Sahbani, W. Bachta, and A. Roby-Brami, "Analysis of hand synergies in healthy subjects during bimanual manipulation of various objects," *J. Neuroeng. Rehabil.*, vol. 11, no. 1, pp. 1–11, 2014, doi: 10.1186/1743-0003-11-113.

[191] M. H. Yun and A. Freivalds, "Analysis of hand tool grips," *Proc. Hum. Factors Ergon. Soc.*, vol. 1, pp. 553–557, 1995.

[192] M. A. M. Berger, A. J. Krul, and H. A. M. Daanen, "Task specificity of finger dexterity tests," *Appl. Ergon.*, vol. 40, no. 1, pp. 145–147, 2009,

doi: 10.1016/j.apergo.2008.01.014.

[193] C. K. Bensel, "The effects of various thicknesses of chemical protective gloves on manual dexterity," *Ergonomics*, vol. 36, no. 6, pp. 687–696, Jun. 1993, doi: 10.1080/00140139308967930.

[194] I. Dianat, C. M. Haslegrave, and A. W. Stedmon, "Using pliers in assembly work: Short and long task duration effects of gloves on hand performance capabilities and subjective assessments of discomfort and ease of tool manipulation," *Appl. Ergon.*, vol. 43, no. 2, pp. 413–423, 2012, doi: 10.1016/j.apergo.2011.06.016.

[195] K. Willms, R. Wells, and H. Carnahan, "Glove attributes and their contribution to force decrement and increased effort in power grip," *Hum. Factors*, vol. 51, no. 6, pp. 797–812, 2009, doi: 10.1177/0018720809357560.

[196] G. E. Torrens and A. Newman, "The evaluation of gloved and ungloved hands," in *Contemporary Ergonomics*, Taylor & Francis, 2000, pp. 301–305.

[197] T. A. Bellingar and A. C. Slocum, "Effect of protective gloves on hand movement: an exploratory study," *Appl. Ergon.*, vol. 24, no. 4, pp. 244–250, Aug. 1993, doi: 10.1016/0003-6870(93)90458-L.

[198] J. B. Nelson and A. Mital, "An ergonomic evaluation of dexterity and tactility with increase in examination/surgical glove thickness," *Ergonomics*, vol. 38, no. 4, pp. 723–733, Apr. 1995, doi: 10.1080/00140139508925144.

[199] W. W. Banks, "The Effects of Degraded Visual and Tactile Information on Diver Work Performance," *Hum. Factors J. Hum. Factors Ergon. Soc.*, vol. 21, no. 4, pp. 409–415, Aug. 1979, doi: 10.1177/001872087902100403.

[200] R. Plummer, T. Stobbe, R. Ronk, W. Myers, H. Kim, and M. Jaraiedi, "Manual Dexterity Evaluation of Gloves Used in Handling Hazardous Materials," *Proc. Hum. Factors Soc. Annu. Meet.*, vol. 29, no. 8, pp. 819–823, Oct. 1985, doi: 10.1177/154193128502900822.

[201] R. C. Oldfield, "The assessment and analysis of handedness," *Neuropsychologia*, vol. 9, no. 1, pp. 97–113, 1971.

[202] G. Westling and R. S. Johansson, "Factors Influencing the Force Control During Precision Grip," *Exp. Brain Res.*, pp. 277–278, 1984.

[203] L. Bronkema-Orr and R. R. Bishu, "The Effects of Glove Frictional Characteristics and Load on Grasp Force and Grasp Control," *Proc. Hum. Factors Ergon. Soc. Annu. Meet.*, vol. 40, no. 13, pp. 702–706, Oct. 1996, doi: 10.1177/154193129604001326.

[204] J. Hermsdörfer, E. Hagl, and D. A. Nowak, "Deficits of anticipatory grip

force control after damage to peripheral and central sensorimotor systems," *Hum. Mov. Sci.*, vol. 23, no. 5, pp. 643–662, 2004, doi: 10.1016/j.humov.2004.10.005.

[205] C. Brogårdh, A. Persson, and B. Sjölund, "Intra- and inter-rater reliability of the Sollerman hand function test in patients with chronic stroke," *Disabil. Rehabil.*, vol. 29, no. 2, pp. 145–154, 2007, doi: 10.1080/09638280600747603.

[206] L. Y. Weng *et al.*, "Excellent reliability of the sollerman hand function test for patients with burned hands," *J. Burn Care Res.*, vol. 31, no. 6, pp. 904–910, 2010, doi: 10.1097/BCR.0b013e3181f93583.

[207] J. M. O'Hara, "The Effect of Pressure Suit Gloves on Hand Performance," *Proc. Hum. Factors Soc. Annu. Meet.*, vol. 33, no. 2, pp. 139–143, Oct. 1989, doi: 10.1177/154193128903300230.

[208] B. S. Lin, I. J. Lee, P. Y. Chiang, S. Y. Huang, and C. W. Peng, "A Modular Data Glove System for Finger and Hand Motion Capture Based on Inertial Sensors," *J. Med. Biol. Eng.*, vol. 39, no. 4, pp. 532–540, 2019, doi: 10.1007/s40846-018-0434-6.

[209] F. M. Sánchez-margallo *et al.*, "Minimally Invasive Therapy & Allied Technologies Application of a motion capture data glove for hand and wrist ergonomic analysis during laparoscopy," vol. 5706, 2014, doi: 10.3109/13645706.2014.925928.

[210] P. H. Holguin, A. A. Rico, L. P. Gomez, and L. M. Munuera, "The Coordinate Movement of the Interphalangeal Joints," *Clin. Orthop. Relat. Res.*, vol. 362, pp. 117–124, May 1999, doi: 10.1097/00003086-199905000-00020.

[211] J. M. Landsmeer, "the Coordination of Finger-Joint Motions.," *J. Bone Joint Surg. Am.*, vol. 45, pp. 1654–1662, 1963, doi: 10.2106/00004623-196345080-00007.

[212] M. Vergara, J. L. Sancho-Bru, V. Gracia-Ibáñez, and A. Pérez-González, "Vergara, M., Sancho-Bru, J. L., Gracia-Ibáñez, V. and Pérez-González, A. (2014) 'An introductory study of common grasps used by adults during performance of activities of daily living', J. Hand Ther. Elsevier, 27, pp. 1–28. doi: 10.1016/j.jht.2014.04.002.," *J. Hand Ther.*, vol. 27, pp. 1–28, Apr. 2014, doi: 10.1016/j.jht.2014.04.002.

[213] I. Carpinella, P. Mazzoleni, M. Rabuffetti, R. Thorsen, and M. Ferrarin, "Experimental protocol for the kinematic analysis of the hand: Definition and repeatability," *Gait Posture*, vol. 23, no. 4, pp. 445–454, 2006, doi: 10.1016/j.gaitpost.2005.05.001.

[214] M. Grebenstein *et al.*, "The hand of the DLR hand arm system: Designed for interaction," *Int. J. Rob. Res.*, vol. 31, no. 13, pp. 1531–1555, 2012, doi: 10.1177/0278364912459209.

[215] M. Bianchi, J. Bohg, and Y. Sun, "Latest Datasets and Technologies Presented in the Workshop on Grasping and Manipulation Datasets," Sep. 2016.

[216] A. Saudabayev, Z. Rysbek, R. Khassenova, and H. A. Varol, "Human grasping database for activities of daily living with depth, color and kinematic data streams," *Sci. Data*, vol. 5, p. 180101, May 2018, doi: 10.1038/sdata.2018.101.

[217] C. Mandery, Ö. Terlemez, M. Do, N. Vahrenkamp, and T. Asfour, "The KIT whole-body human motion database," *Proc. 17th Int. Conf. Adv. Robot. ICAR 2015*, vol. 611909, no. 611909, pp. 329–336, 2015, doi: 10.1109/ICAR.2015.7251476.

[218] A. Roda-Sales, M. Vergara, J. L. Sancho-Bru, V. Gracia-Ibáñez, and N. J. Jarque-Bou, "Mendeley Data." 2019, doi: http://dx.doi.org/10.17632/8mf4y2srgh.

[219] G. Wu *et al.*, "ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: Shoulder, elbow, wrist and hand," *J. Biomech.*, vol. 38, no. 5, pp. 981–992, 2005, doi: 10.1016/j.jbiomech.2004.05.042.

[220] A. I. Kapandji, *The Physiology of the Joints. Volume I: Upper Limb*, 5th ed. 1998.

[221] P. W. Brand and A. M. Hollister, *Clinical Mechanics of the Hand*. St. Louis: Mosby Publishing, 1999.

[222] A. Roda-Sales, M. Vergara, J. L. Sancho-Bru, V. Gracia-Ibáñez, and N. J. Jarque-Bou, "Human hand kinematic data during feeding and cooking tasks," *Sci. Data*, vol. 6, no. 1, 2019, doi: 10.1038/s41597-019-0175-6.

[223] J. Yong, J. C. MacDermid, T. Packham, P. Bobos, J. Richardson, and S. Moll, "Performance-based outcome measures of dexterity and hand function in person with hands and wrist injuries: A scoping review of measured constructs," *J. Hand Ther.*, 2021, doi: 10.1016/j.jht.2021.04.017.

[224] E. Niechwiej-Szwedo, M. Nouredanesh, and J. Tung, "Test-retest repeatability reveals a temporal kinematic signature for an upper limb precision grasping task in adults," *Hum. Mov. Sci.*, vol. 75, no. October 2020, p. 102721, 2021, doi: 10.1016/j.humov.2020.102721.

[225] V. Gracia-Ibáñez, J. L. Sancho-Bru, M. Vergara, A. Roda-Sales, N. J. Jarque-Bou, and V. Bayarri-Porcar, "Biomechanical function requirements of the wrist. Circumduction versus flexion/abduction range of motion," *J. Biomech.*, vol. 110, 2020, doi: 10.1016/j.jbiomech.2020.109975.

[226] H.-I. Ma, W.-J. Hwang, P.-L. Tsai, and Y.-W. Hsu, “The effect of eating utensil weight on functional arm movement in people with Parkinson’s disease: a controlled clinical trial,” *Clin. Rehabil.*, vol. 23, no. 12, pp. 1086–1092, Dec. 2009, doi: 10.1177/0269215509342334.

[227] D. Lee, M. T. Van Holsbeeck, P. K. Janevski, D. L. Ganos, D. M. Ditmars, and V. B. Darian, “Diagnosis of carpal tunnel syndrome: Ultrasound versus electromyography,” *Radiol. Clin. North Am.*, vol. 37, no. 4, pp. 859–872, 1999, doi: 10.1016/S0033-8389(05)70132-9.

[228] G. A. Broe *et al.*, “Impact of chronic systemic and neurological disorders on disability, depression and life satisfaction,” *Int. J. Geriatr. Psychiatry*, vol. 13, no. 10, pp. 667–673, 1998, doi: 10.1002/(SICI)1099-1166(1998100)13:10<667::AID-GPS839>3.0.CO;2-G.

[229] G. Robinson-Smith, M. V. Johnston, and J. Allen, “Self-care self-efficacy, quality of life, and depression after stroke,” *Arch. Phys. Med. Rehabil.*, vol. 81, no. 4, pp. 460–464, 2000, doi: 10.1053/mr.2000.3863.

[230] J. C. Millán-Calenti *et al.*, “Prevalence of functional disability in activities of daily living (ADL), instrumental activities of daily living (IADL) and associated factors, as predictors of morbidity and mortality,” *Arch. Gerontol. Geriatr.*, vol. 50, no. 3, pp. 306–310, 2010, doi: 10.1016/j.archger.2009.04.017.

[231] L. R. Ramos, E. J. Simoes, and M. S. Albert, “Dependence in activities of daily living and cognitive impairment strongly predicted mortality in older urban residents in Brazil: A 2-year follow-up,” *J. Am. Geriatr. Soc.*, vol. 49, no. 9, pp. 1168–1175, 2001, doi: 10.1046/j.1532-5415.2001.49233.x.

[232] W. K. Scott, C. A. Macera, C. B. Cornman, and P. A. Sharpe, “Functional health status as a predictor of mortality in men and women over 65,” *J. Clin. Epidemiol.*, vol. 50, no. 3, pp. 291–296, 1997, doi: 10.1016/S0895-4356(96)00365-4.

[233] World Health Organization, “Assistive devices and technologies,” 2019. https://www.who.int/disabilities/technology/en/ (accessed Aug. 09, 2019).

[234] T. M. Long, M. Woolverton, D. F. Perry, and M. J. Thomas, “Training Needs of Pediatric Occupational Therapists in Assistive Technology,” *Am. J. Occup. Ther.*, vol. 61, no. 3, pp. 345–354, May 2007, doi: 10.5014/ajot.61.3.345.

[235] L. H. Kraskowsky and M. Finlayson, “Factors Affecting Older Adults’ Use of Adaptive Equipment: Review of the Literature,” *Am. J. Occup. Ther.*, vol. 55, no. 3, pp. 303–310, May 2001, doi: 10.5014/ajot.55.3.303.

[236] T. Hoffmann and K. McKenna, “A Survey of Assistive Equipment Use by Older People following Hospital Discharge,” *Br. J. Occup. Ther.*, vol.

67, no. 2, pp. 75–82, Feb. 2004, doi: 10.1177/030802260406700204.

[237] W. C. Mann, D. Hurren, and M. Tomita, “Comparison of Assistive Device Use and Needs of Home-Based Older Persons With Different Impairments,” *Am. J. Occup. Ther.*, vol. 47, no. 11, pp. 980–987, Nov. 1993, doi: 10.5014/ajot.47.11.980.

[238] A. Roda-Sales, M. Vergara, J. L. Sancho-Bru, V. Gracia-Ibáñez, and N. J. Jarque-Bou, “Effect of assistive devices on hand and arm posture during activities of daily living,” *Appl. Ergon.*, vol. 76, no. December 2018, pp. 64–72, 2019, doi: 10.1016/j.apergo.2018.12.003.

[239] R. C. Holt and R. J. Holt, “Gerotechnology: Kitchen aids,” *Eur. Geriatr. Med.*, vol. 2, no. 4, pp. 256–262, 2011, doi: 10.1016/j.eurger.2011.01.019.

[240] R. Hepherd, “Aids for bathing and showering,” *Eur. Geriatr. Med.*, vol. 2, no. 3, pp. 190–193, 2011, doi: 10.1016/j.eurger.2011.02.006.

[241] D. Harman and S. Craigie, “Gerotechnology series: Toileting aids,” *Eur. Geriatr. Med.*, vol. 2, no. 5, pp. 314–318, 2011, doi: 10.1016/j.eurger.2011.01.017.

[242] S. Stowe, J. Hopes, and G. Mulley, “Gerotechnology series: 2. Walking aids,” *Eur. Geriatr. Med.*, vol. 1, no. 2, pp. 122–127, 2010, doi: 10.1016/j.eurger.2010.02.003.

[243] H. Hemmingsson, H. Lidstrom, and L. Nygard, “Use of Assistive Technology Devices in Mainstream Schools: Students’ Perspective,” *Am. J. Occup. Ther.*, vol. 63, no. 4, pp. 463–472, Jul. 2009, doi: 10.5014/ajot.63.4.463.

[244] T. Wielandt, K. Mckenna, L. Tooth, and J. Strong, “Factors that predict the post-discharge use of recommended assistive technology (AT),” *Disabil. Rehabil. Assist. Technol.*, vol. 1, no. 1–2, pp. 29–40, Jan. 2006, doi: 10.1080/09638280500167159.

[245] C. Skymne, S. Dahlin-Ivanoff, L. Claesson, and K. Eklund, “Getting used to assistive devices: Ambivalent experiences by frail elderly persons,” *Scand. J. Occup. Ther.*, vol. 19, no. 2, pp. 194–203, Mar. 2012, doi: 10.3109/11038128.2011.569757.

[246] K. T. Yeung, C. H. Lin, Y. L. Teng, F. F. Chen, S. Z. Lou, and C. L. Chen, “Use of and self-perceived need for Assistive devices in individuals with disabilities in Taiwan,” *PLoS One*, vol. 11, no. 3, pp. 1–13, 2016, doi: 10.1371/journal.pone.0152707.

[247] G. C. David, “Ergonomic methods for assessing exposure to risk factors for work-related musculoskeletal disorders,” *Occup. Med. (Chic. Ill).*, vol. 55, no. 3, pp. 190–199, May 2005, doi: 10.1093/occmed/kqi082.

[248] C. E. Chaisson *et al.*, “Radiographic hand osteoarthritis: incidence, patterns, and influence of pre-existing disease in a population based

sample.," *J. Rheumatol.*, vol. 24, no. 7, pp. 1337–43, Jul. 1997, [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/9228134.

[249] I. Kjeken *et al.*, "Activity limitations and participation restrictions in women with hand osteoarthritis: Patients' descriptions and associations between dimensions of functioning," *Ann. Rheum. Dis.*, vol. 64, no. 11, pp. 1633–1638, 2005, doi: 10.1136/ard.2004.034900.

[250] I. Shipham, "Rheumatoid arthritis: hand function, activities of daily living, grip strength and essential assistive devices.," *Curationis*, vol. 26, no. 3, pp. 98–106, Sep. 2003, doi: 10.4102/curationis.v26i3.857.

[251] P. da S. Santos *et al.*, "Use of assistive devices by individuals with hands osteoarthritis," *Cad. Bras. Ter. Ocup.*, vol. 26, no. 1, pp. 145–152, 2018, doi: 10.4322/2526-8910.ctoAO0999.

[252] D. H. Gates, L. S. Walters, J. Cowley, J. M. Wilken, and L. Resnik, "Range of Motion Requirements for Upper-Limb Activities of Daily Living," *Am. J. Occup. Ther.*, vol. 70, no. 1, p. 7001350010p1, Dec. 2015, doi: 10.5014/ajot.2016.015487.

[253] H. Igo Krebs, N. Hogan, M. L. Aisen, and B. T. Volpe, "Robot-aided neurorehabilitation," *IEEE Trans. Rehabil. Eng.*, vol. 6, no. 1, pp. 75–87, 1998, doi: 10.1109/86.662623.

[254] C. Bosecker, L. Dipietro, B. Volpe, and H. Igo Krebs, "Kinematic Robot-Based Evaluation Scales and Clinical Counterparts to Measure Upper Limb Motor Performance in Patients With Chronic Stroke," *Neurorehabil. Neural Repair*, vol. 24, no. 1, pp. 62–69, 2010, doi: 10.1177/1545968309343214.

[255] N. Smania *et al.*, "Active finger extension: A simple movement predicting recovery of arm function in patients with acute stroke," *Stroke*, vol. 38, no. 3, pp. 1088–1090, 2007, doi: 10.1161/01.STR.0000258077.88064.a3.

[256] A. P. Sangole and M. F. Levin, "Palmar arch dynamics during reach-to-grasp tasks," *Exp. Brain Res.*, vol. 190, no. 4, pp. 443–452, Oct. 2008, doi: 10.1007/s00221-008-1486-6.

[257] M. Alt Murphy and C. K. Häger, "Kinematic analysis of the upper extremity after stroke – how far have we reached and what have we grasped?," *Phys. Ther. Rev.*, vol. 20, no. 3, pp. 137–155, 2015, doi: 10.1179/1743288X15Y.0000000002.

Appendix I

This appendix presents the calibration protocol of the instrumented gloves CyberGlove used in the Biomechanics and Ergonomics Research Group, adapted from the original protocol by Gracia-Ibáñez et al. [23].

The calibration protocol of the CyberGlove instrumented glove consists in 73 recordings (Table AI.1 and AI.2):

- **cal01 to cal15:** Recordings to calibrate the wrist gauges (13 static postures and 2 dynamic recordings).
- **cal16 to cal35:** Recordings to calibrate PIP and MCP gauges (20 static postures).
- **cal36 to cal59:** Static and dynamic postures to calibrate finger abduction gauges and CMC gauges.
- **cal60 to cal65:** Recordings of static postures to check calibration.
- **cal66 to cal73:** Static postures to calibrate DIP gauges (8 static postures only required in case of calibrating the 22DoF CyberGlove).

Table AI.1. ID of the recordings from cal1 to cal65 ("F" for flexion, "dev" for wrist deviation)

ID	POSTURE	
Cal01	wrist	F=0 dev=0
Cal02	wrist	F=0 dev=10rad
Cal03	wrist	F=0 dev=20rad
Cal04	wrist	F=0 dev=10cub
Cal05	wrist	F=0 dev=20cub
Cal06	wrist	F=0 dev=0/20rad/20cub/0
Cal07	wrist	F=-30 dev=0
Cal08	wrist	F=-30 dev=20rad
Cal09	wrist	F=-30 dev=20cub
Cal10	wrist	F=-60 dev=0
Cal11	wrist	F=30 dev=0
Cal12	wrist	F=30 dev=20rad
Cal13	wrist	F=30 dev=20cub
Cal14	wrist	F=30/-x/30 dev=0
Cal15	wrist	F=60 dev=0
cal16	PIP1	0º
cal17	PIP1	75º
Cal18	PIP2	0º
Cal19	PIP2	75º
Cal20	PIP3	0º
Cal21	PIP3	75º
Cal22	PIP4	0º
Cal23	PIP4	75º
Cal24	PIP5	0º
Cal25	PIP5	75º
Cal26	MCP1	0º
Cal27	MCP1	35º
Cal28	MCP2	0º
Cal29	MCP2	75º
Cal30	MCP3	0º
Cal31	MCP3	75º
Cal32	MCP4	0º
Cal33	MCP4	75º
Cal34	MCP5	0º
Cal35	MCP5	75º
Cal36	Flat closed hand (palmar arch)	
Cal37	Flat relaxed hand	
Cal38	Fixed abduction 2-4-5 hand	
Cal39	Fing2Mov	0º
Cal40	Fing2Mov	40º
Cal41	Fing2Mov	80º
Cal42	Fing2Fixed	0º
Cal43	Fing2Fixed	40º
Cal44	Fing2Fixed	80º
Cal45	Fing2+3Mov	0º
Cal46	Fing2+3Mov	40º
Cal47	Fing2+3Mov	80º
Cal48	Fing2+3Fixed	0º
Cal49	Fing2+3Fixed	40º
Cal50	Fing2+3Fixed	80º
Cal51	Fing2+3+4Mov	0º
Cal52	Fing2+3+4Mov	40º
Cal53	Fing2+3+4Mov	80º

Cal54	Fing2+3+4Fixed 0º
Cal55	Fing2+3+4Fixed 40º
Cal56	Fing2+3+4Fixed 80º
Cal57	extension-flexion CMC1
Cal58	adduction-abduction CMC1
Cal59	Circle1-2
Cal60	Flat extended hand
Cal61	Max. ext. MCP1
Cal62	Sphere grasp
Cal63	American sign Y
Cal64	American sign R
Cal65	Max. Palmar Arch

Table AI.2. ID of the recordings from cal66 to cal73 ("F" for flexion, "dev" for wrist deviation)

ID	POSTURE
Cal66	DIP2 0º
Cal67	DIP2 75º
Cal68	DIP3 0º
Cal79	DIP3 75º
Cal70	DIP4 0º
Cal71	DIP4 75º
Cal72	DIP5 0º
Cal73	DIP5 75º

AI.1 Postures and movements to record

1. Recordings from cal01 to cal15:

These first recordings will be used to calibrate the wrist flexion and abduction gauges. The use of a specific sheet with printed deviation angles will be required, as well as wooden pieces to configure wrist flexion angle. Subject's forearm must be centred in the marks of the sheet.

These recordings can be divided in three parts:

- <u>Recordings with F=0</u>

  Static postures with F=0 and several deviations (0º, -10º, -20º, 10º, 20º) (Figure AI.1).

Figure AI.1: Static postures with F=0.

After this, a dynamic recording will be performed, where subject will go from 0º deviation to -30º, 30º and back to 0º, maintaining flexion at 0º.

- <u>Recordings with F=-30</u>

  Static postures with F=-30º and deviations of 0º, -20º and 20º will be recorded (Figure AI.2).

Figure AI.2: Static postures with F=-30º

- <u>Recording with F=-60º and dev=0º</u>

  A static posture with F=-60º and null deviation will be recorded (Figure AI.3).

Figure AI.3: Static posture with F=-60º and dev=0º

- <u>Recordings with F=30</u>

  Static postures with F=30º and deviations of 0º, -20º and 20º will be recorded (Figure AI.4).

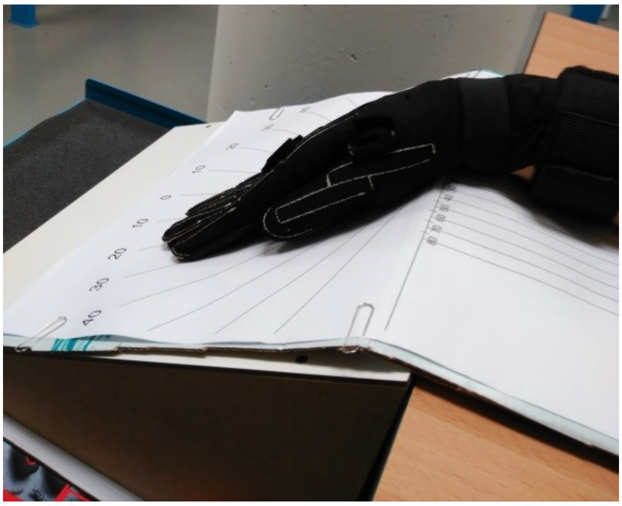


Figure AI.4: Static postures with F=30º

- <u>Recording with F=60º and dev=0º</u>

  A static posture with F=60º and null deviation will be recorded (Figure AI.5).

Figure AI.5: Static posture with F=60º

2. **Recordings from cal16 to cal35:**

- <u>Static postures from cal16 to cal25</u>: PIP joints from thumb to little fingers will be recorded maintaining two controlled flexion angles (0º and 75º) using specific wooden pieces (Figure AI.6).

PIP 1_0º.

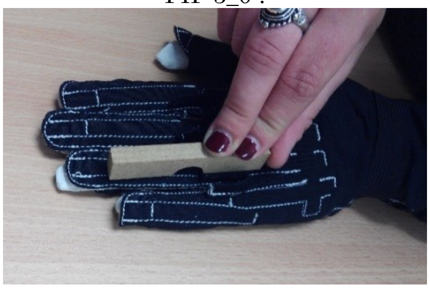
PIP 1_75º.

PIP 2_0º.

PIP 2_75º.

PIP 3_0º.

PIP 3_75º.



PIP 4_0º.

PIP 4_75º.

PIP 5_0º.

PIP 6_75º.

Figure AI.6: Static postures for PIP gauges calibration.

- <u>Static postures from cal26 to cal35:</u> MCP joints from thumb to little fingers will be recorded maintaining two controlled flexion angles (0º and 75º, except of thumb MCP, with 0º and 35º) using specific wooden pieces (Figure AI.7).

MCP 1_0º.

MCP 1_35º.

MCP 2_0º.

MCP 2_75º.

MCP 3_0º.

MCP 3_75º.

MCP 4_0º.

MCP 4_75º.

MCP 5_0º.

MCP 6_75º.

Figure AI.7: Static postures for MCP gauges calibration.

3. Recordings from cal36 to cal38:

Static postures with the reference posture (null finger abduction, see Figure AI.8 left), relaxed flat hand (Figure AI.8 right) and controlled abduction of index, middle and little fingers (Figure AI.9).

Palmar arch must be measured with a goniometer when subject is performing the null finger abduction posture.

The fixed abduction posture must be performed locating specific polymeric pieces between fingers, in order to control the abduction angles.

Reference: flat hand and fingers together

Flat relaxed hand

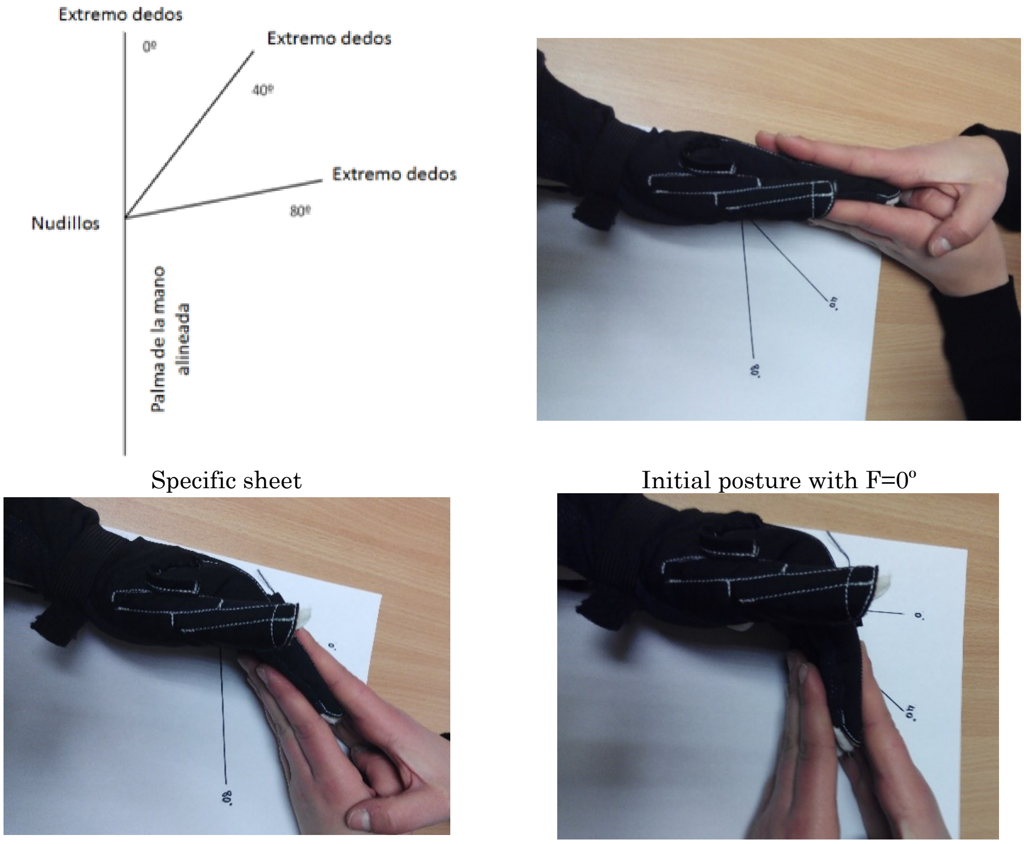
Figure AI.8: Reference and flat relaxed hand postures.

Figure AI.9. Static posture to calibrate MCP joints gauges.

4. Recordings from cal39 to cal56:

Dynamic recordings to compensate the effect of flexion in the MCP abduction gauges.

Starting from different initial MCP flexions (0º, 40º and 80º), hand must be located in a specific sheet and each finger must perform extension and flexion movements (Figure AI.10).



Specific sheet

Initial posture with F=0º

Initial posture with F=40º

Initial posture with F=80º

Figure AI.10. Initial postures for dynamic recordings to calibrate MCP abduction gauges.

The movements will be performed with different configurations of fingers (e.g. cal39 consists in moving index finger and holding middle, ring and little fingers, starting from a previous MCP flexion of 40º). All the finger and posture combinations are detailed in Table AI.3 and figure AI.11.

Table AI.3: Dynamic postures of recordings from cal39 to cal56.

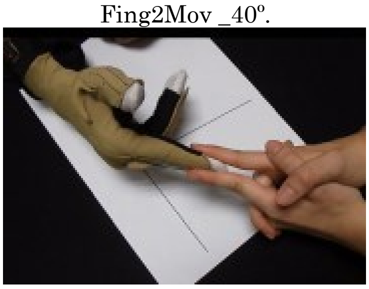
Cal39	Fing2Mov	0º
Cal40	Fing2Mov	40º
Cal41	Fing2Mov	80º
Cal42	Fing2Fixed	0º
Cal43	Fing2Fixed	40º
Cal44	Fing2Fixed	80º
Cal45	Fing2+3Mov	0º
Cal46	Fing2+3Mov	40º
Cal47	Fing2+3Mov	80º
Cal48	Fing2+3Fixed	0º
Cal49	Fing2+3Fixed	40º
Cal50	Fing2+3Fixed	80º
Cal51	Fing2+3+4Mov	0º
Cal52	Fing2+3+4Mov	40º
Cal53	Fing2+3+4Mov	80º
Cal54	Fing2+3+4Fixed	0º
Cal55	Fing2+3+4Fixed	40º
Cal56	Fing2+3+4Fixed	80º


Fing2Mov _0º.


Fing2Mov _40º.


Fing2Mov _80º.


Fing2Fixed _0º.

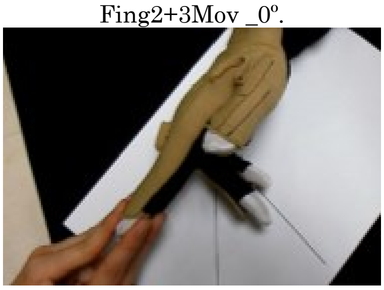

Fing2Fixed _40º.


Fing2Fixed _80º.


Fing2+3Mov _0º.


Fing2+3Mov _40º.


Fing2+3Mov _80º.


Fing2+3Fixed _0º.


Fing2+3Fixed _40º.


Fing2+3Fixed _80º.


Fing2+3+4Mov _0º.


Fing2+3+4Mov _40º.


Fing2+3+4Mov _80º.


Fing2+3+4Fixed _0º.

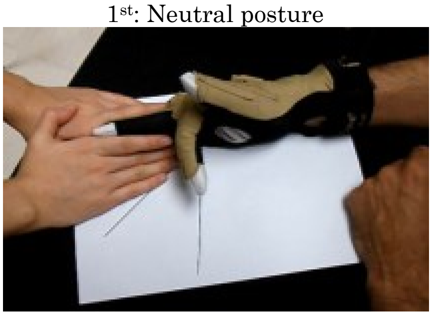

Fing2+3+4Fixed _40º.


Fing2+3+4Fixed _80º.

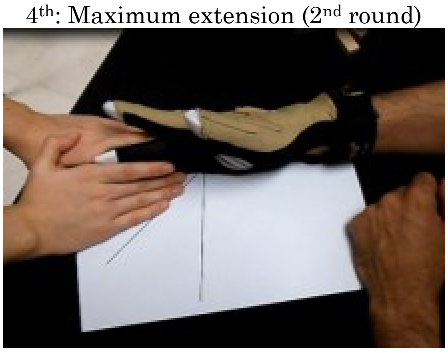
Figure AI.11: Dynamic postures of recordings from cal39 to cal56.

Subject must start each recording from the reference posture (MCP flexion of 0º, 40º or 80º) and perform the maximum MCP extension, and then, the maximum flexion, repeating this movement three times and going back to the neutral posture (Figure AI.12).

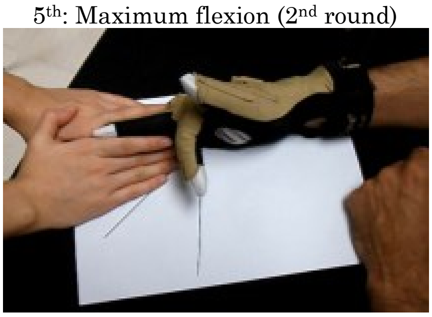
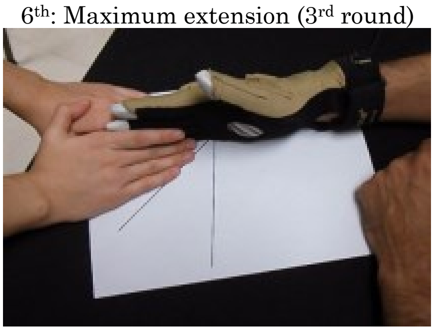

1st: Neutral posture 2nd: Maximum extension




3rd: Maximum flexion 4th: Maximum extension (2nd round)

5th: Maximum flexion (2nd round) 6th: Maximum extension (3rd round)

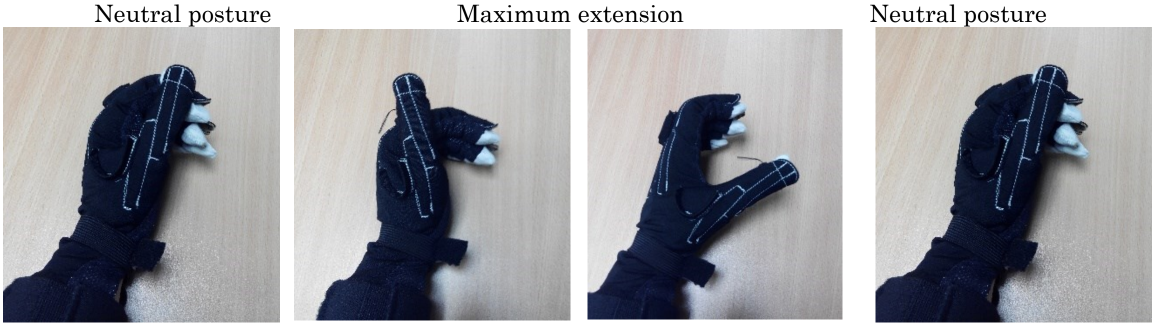
7th: Maximum flexion (3rd round) 8th: Initial posture

Figure AI.12: Complete movement when calibrating index MCP gauge (cal39).

5. Recordings cal57 and cal58:

Dynamic postures for the calculation of thumb CMC flexion and abduction. In the first one (cal57), starting from the neutral posture (Figure AI.13, top), subject must reach the maximum thumb extension and going back to the neutral posture. Then, in cal58, from neutral posture subject must reach the maximum adduction, the maximum abduction and going back to neutral posture (Figure AI.13, bottom).

Neutral posture | Maximum extension | Neutral posture



Neutral posture | Maximum abduction | Maximum adduction | Neutral posture

Figure AI.13: Dynamic recordings cal57 (top) and cal58 (bottom).

6. Recording cal59

Dynamic posture to calculate the flexion and abduction of thumb CMC (Figure AI.14). It consists in starting from a posture where thumb and index fingertips are in contact in a o-shaped posture. Then, both fingers must be extended at maximum, but without separating both fingertips. After this, subject must perform the initial o-shaped posture. This movement must be repeated three times.

O-shaped posture | Extended posture

Figure AI.14: Dynamic recording to calibrate thumb CMC gauge.

AI.2 Static postures to check the goodness of the calibration

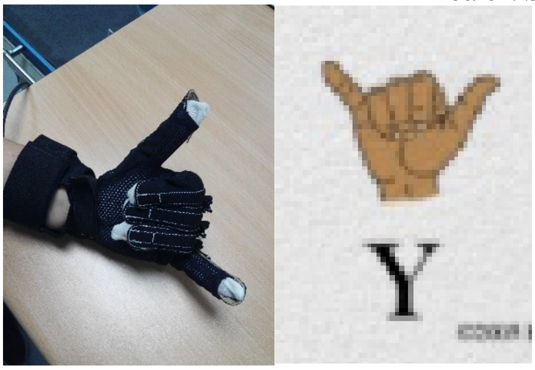
After all the recordings required to calibrate the 18DoF CyberGlove, five static postures (cal60 to cal65) must be recorded, in order to check the goodness of the coefficients obtained in the calibration process (Figure AI.15).

In posture cal65, where subject is asked to perform a posture with maximum palmar angle (thumb and little fingertips together), palmar arching must be measured with a goniometer and annotated.

Cal60: Flat extended hand.

Cal61: Maximum MCP extension posture.

Cal62: Sphere grasp



Cal63: American sign language Y

Cal64: American sign language R

Cal65: Maximum palmar arch posture.

Figure AI.15: Static postures to check the goodness of the calibration.

AI.3 Distal interphalangeal joint calibration postures

In order to calibrate the DIP joints of the 22DoF CyberGlove, eight additional recordings were added to the original 18DoF CyberGlove calibration protocol. These recordings consist in static postures similar to the ones performed to calibrate the PIP joints, but in this case, maintaining in fingers from index to little postures of flexion 0º and 75º.

Appendix II

This appendix contains the plots corresponding to the analyses performed in section 3.4. (Relationship between proximal and distal interphalangeal joint angles). Specifically, the plots presented are:

- *Scatter plots of the mean absolute error in each finger when estimating DIP joint angles from PIP ones using ADL_M coefficients assuming null and non-null constant coefficient, both in the phases of ADL_R and ADL_M.*

- *Scatter plots of index finger PIP and DIP angles recorded during FMT, for each subject and finger.*

- *Box and whiskers plots of error obtained in each task during ADL_M and ADL_R when estimating the index DIP angle from the PIP one using the coefficients obtained during FMT and during ADL_M.*

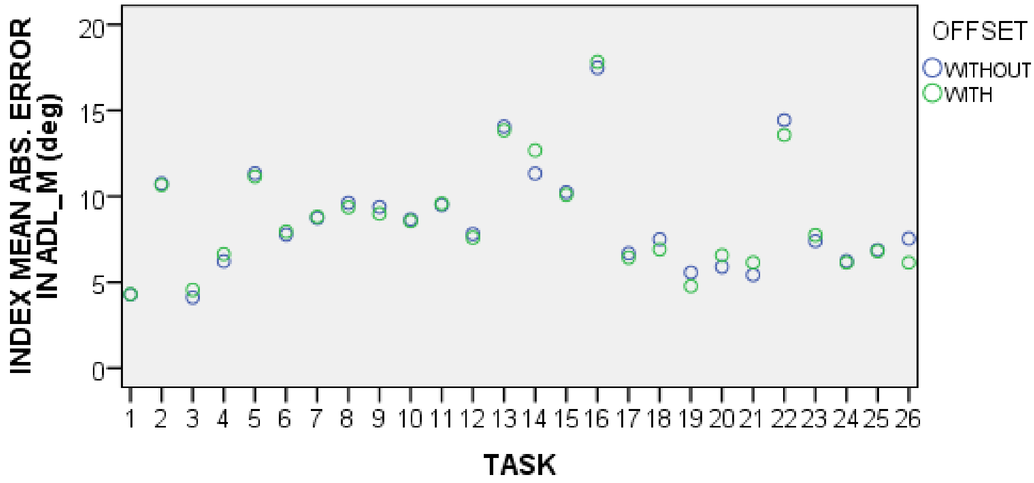


Figure AII.1: Scatter plots of index finger mean absolute error (in degrees) when estimating DIP angles from PIP ones in ADL_M using coefficients obtained when performing regressions with ADL_M data assuming null constant coefficient (without offset) and non-null constant coefficient (with offset). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

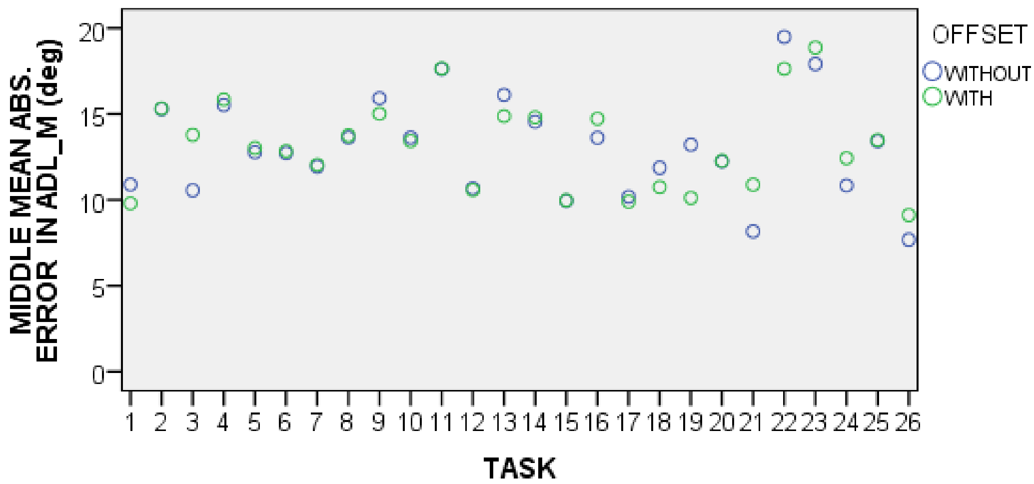


Figure AII.2: Scatter plots of middle finger mean absolute error (in degrees) when estimating DIP angles from PIP ones in ADL_M using coefficients obtained when performing regressions with ADL_M data assuming null constant coefficient (without offset) and non-null constant coefficient (with offset). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

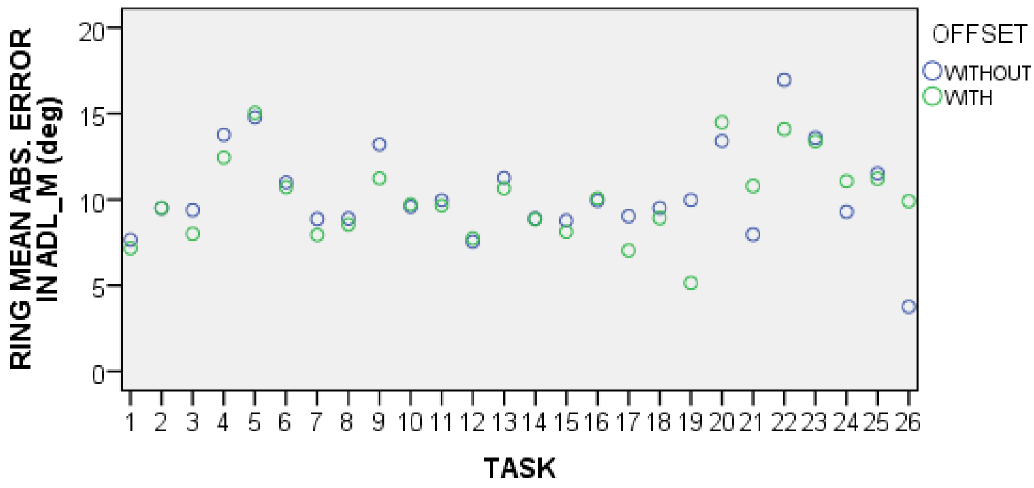


Figure AII.3: Scatter plots of ring finger mean absolute error (in degrees) when estimating DIP angles from PIP ones in ADL_M using coefficients obtained when performing regressions with ADL_M data assuming null constant coefficient (without offset) and non-null constant coefficient (with offset). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

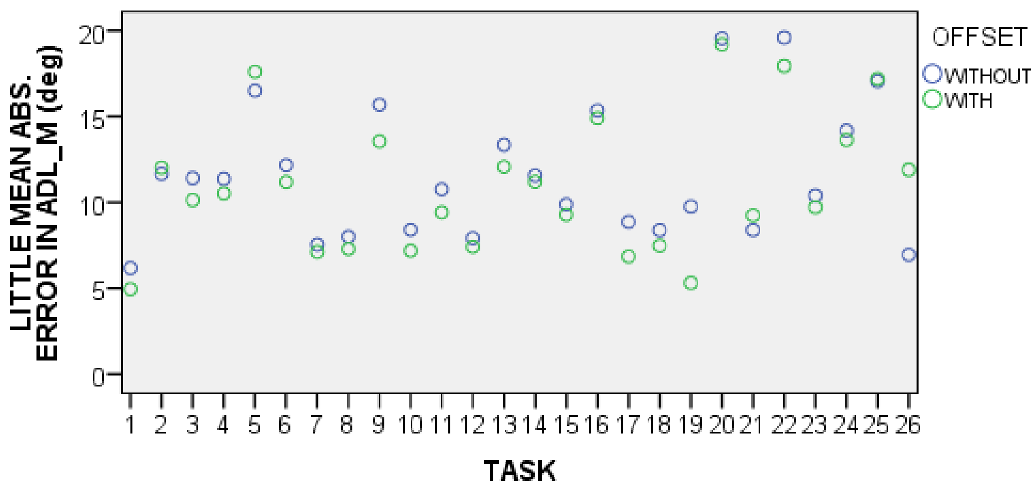


Figure AII.4: Scatter plots of little finger mean absolute error (in degrees) when estimating DIP angles from PIP ones in ADL_M using coefficients obtained when performing regressions with ADL_M data assuming null constant coefficient (without offset) and non-null constant coefficient (with offset). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

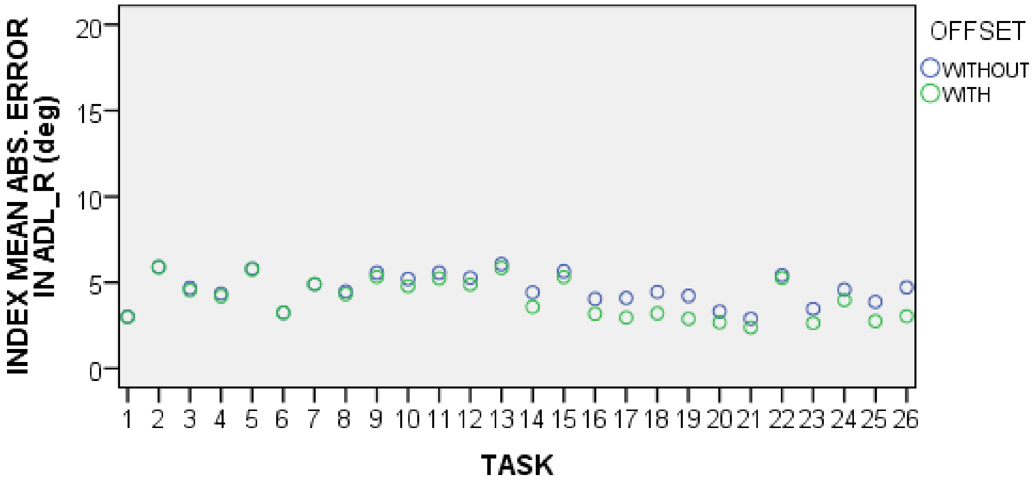


Figure AII.5: Scatter plots of index finger mean absolute error (in degrees) when estimating DIP angles from PIP ones in ADL_M using coefficients obtained when performing regressions with ADL_R data assuming null constant coefficient (without offset) and non-null constant coefficient (with offset). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

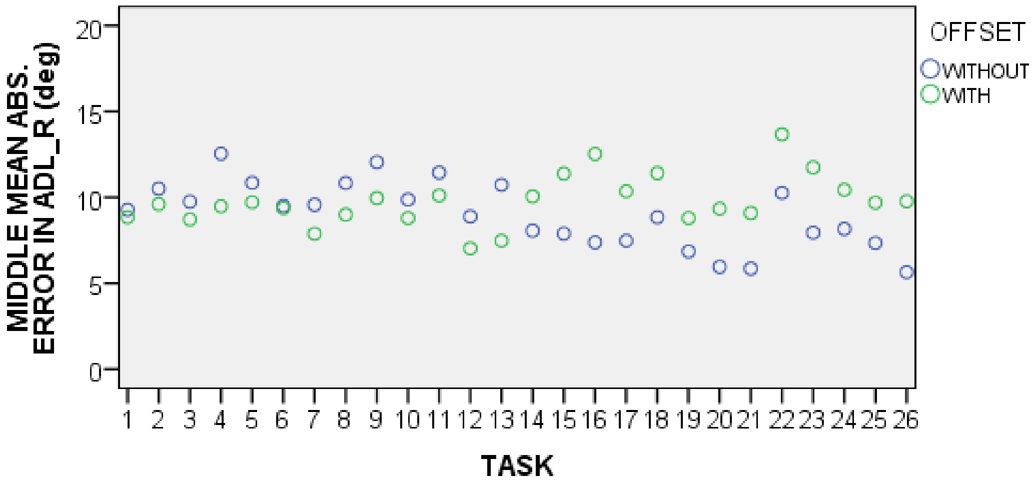


Figure AII.6: Scatter plots of middle finger mean absolute error (in degrees) when estimating DIP angles from PIP ones in ADL_M using coefficients obtained when performing regressions with ADL_R data assuming null constant coefficient (without offset) and non-null constant coefficient (with offset). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

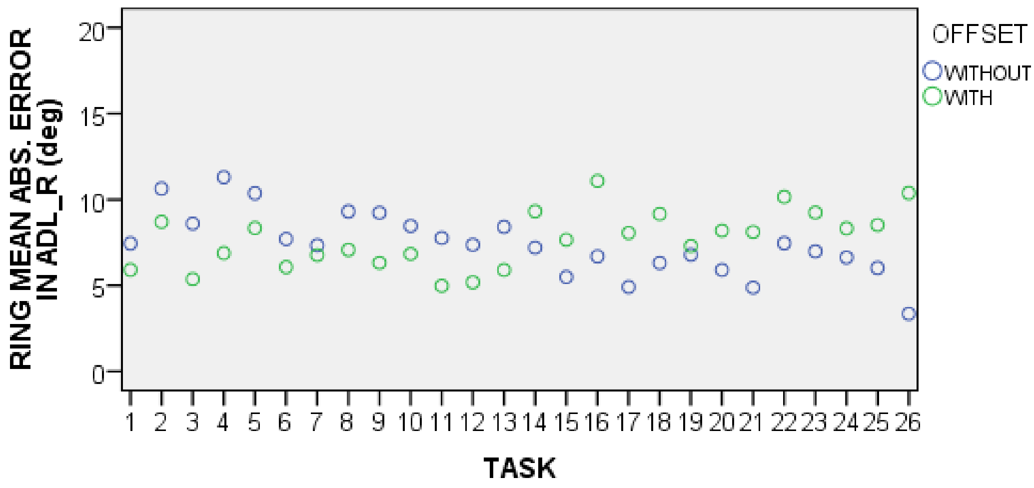


Figure AII.7: Scatter plots of ring finger mean absolute error (in degrees) when estimating DIP angles from PIP ones in ADL_M using coefficients obtained when performing regressions with ADL_R data assuming null constant coefficient (without offset) and non-null constant coefficient (with offset). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

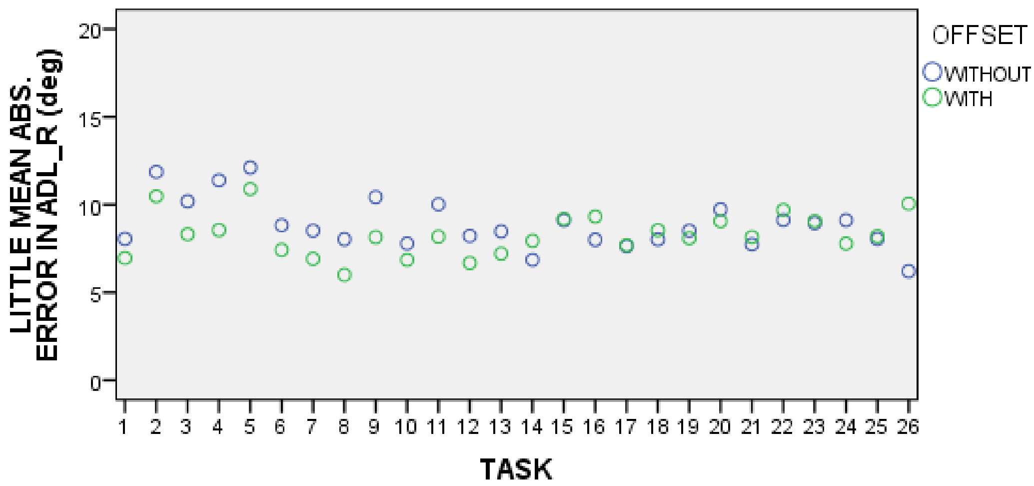


Figure AII.8: Scatter plots of little finger mean absolute error (in degrees) when estimating DIP angles from PIP ones in ADL_M using coefficients obtained when performing regressions with ADL_R data assuming null constant coefficient (without offset) and non-null constant coefficient (with offset). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

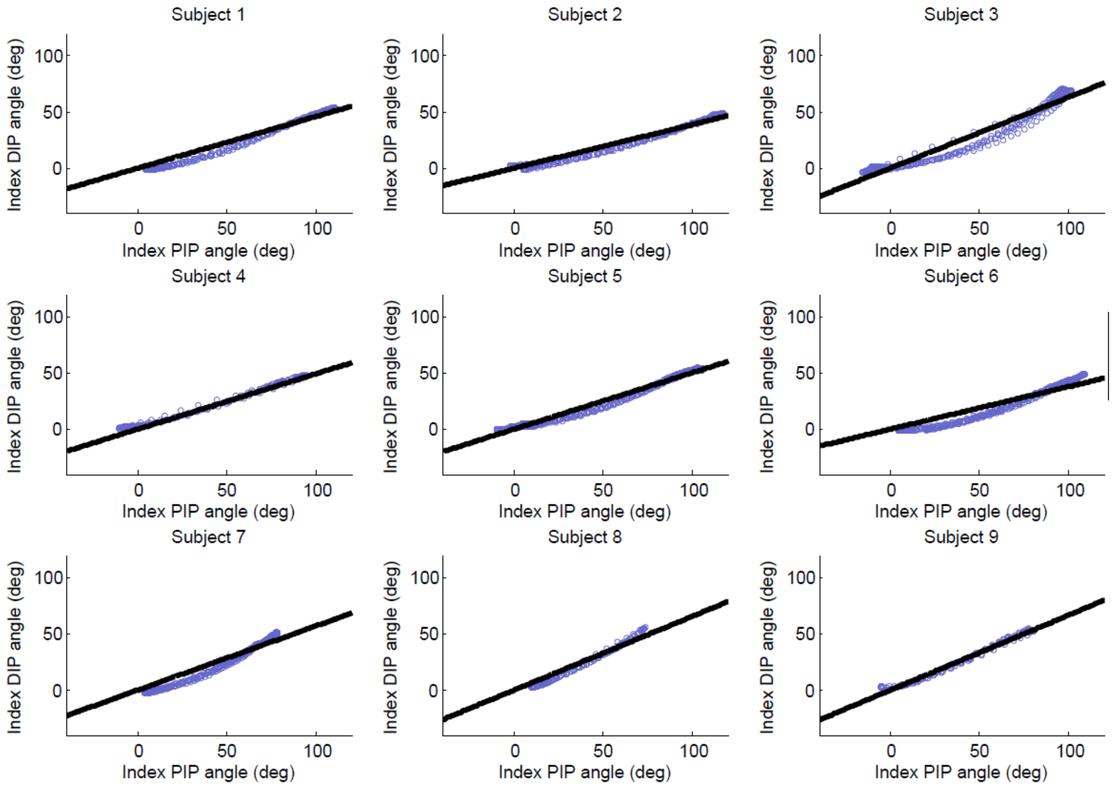


Figure AII.9: Scatter plots of index finger PIP and DIP angles recorded (in degrees) during FMT, for each subject. Regression line of each subject's data plotted in black.

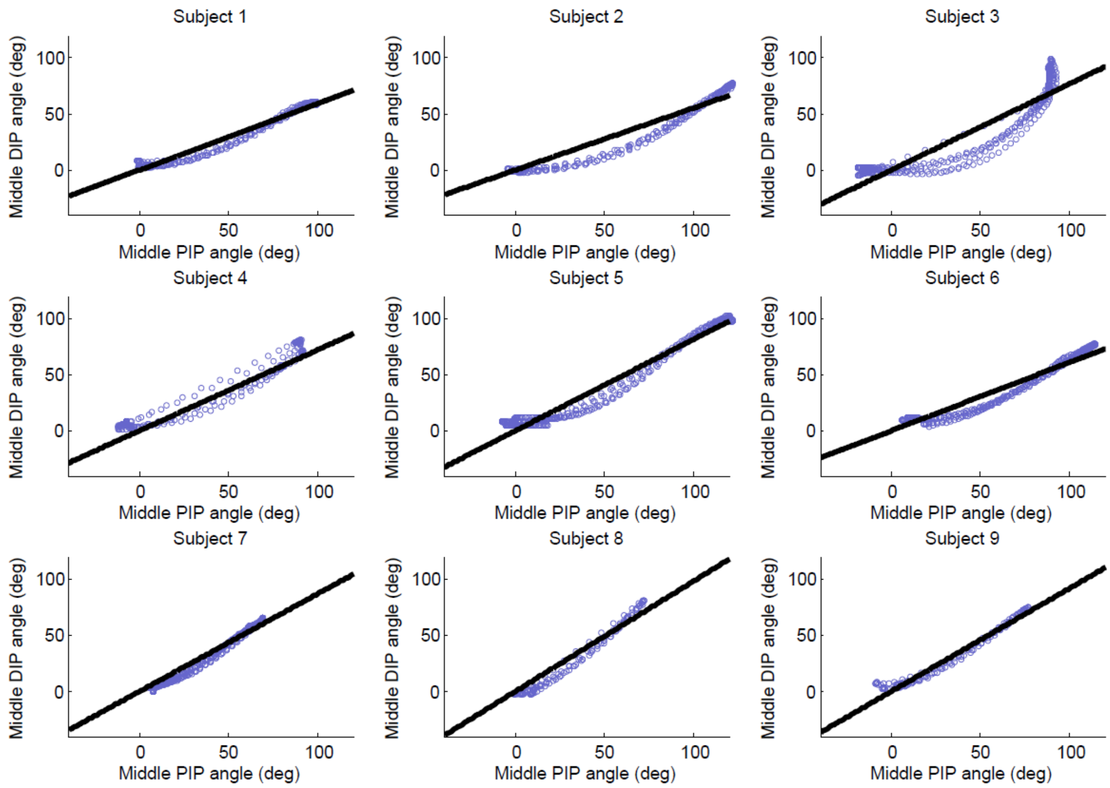


Figure AII.10: Scatter plots of middle finger PIP and DIP angles recorded (in degrees) during FMT, for each subject. Regression line of each subject's data plotted in black.

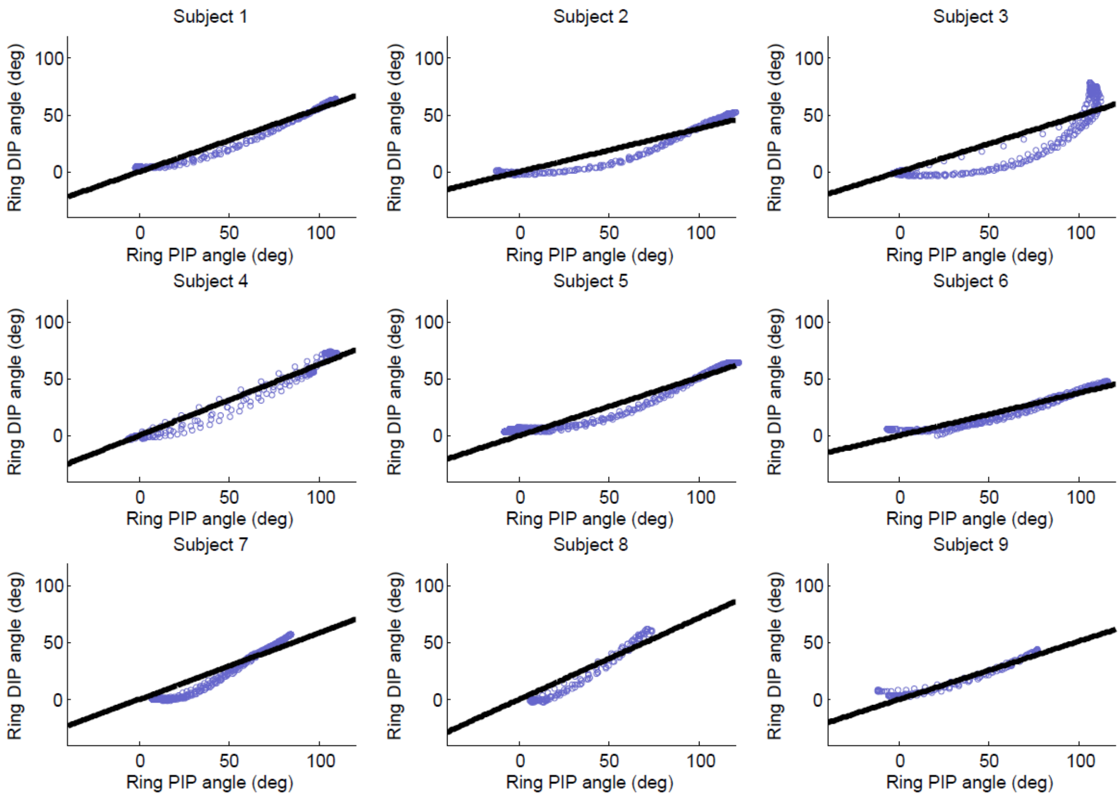


Figure AII.11: Scatter plots of ring finger PIP and DIP angles recorded (in degrees) during FMT, for each subject. Regression line of each subject's data plotted in black.

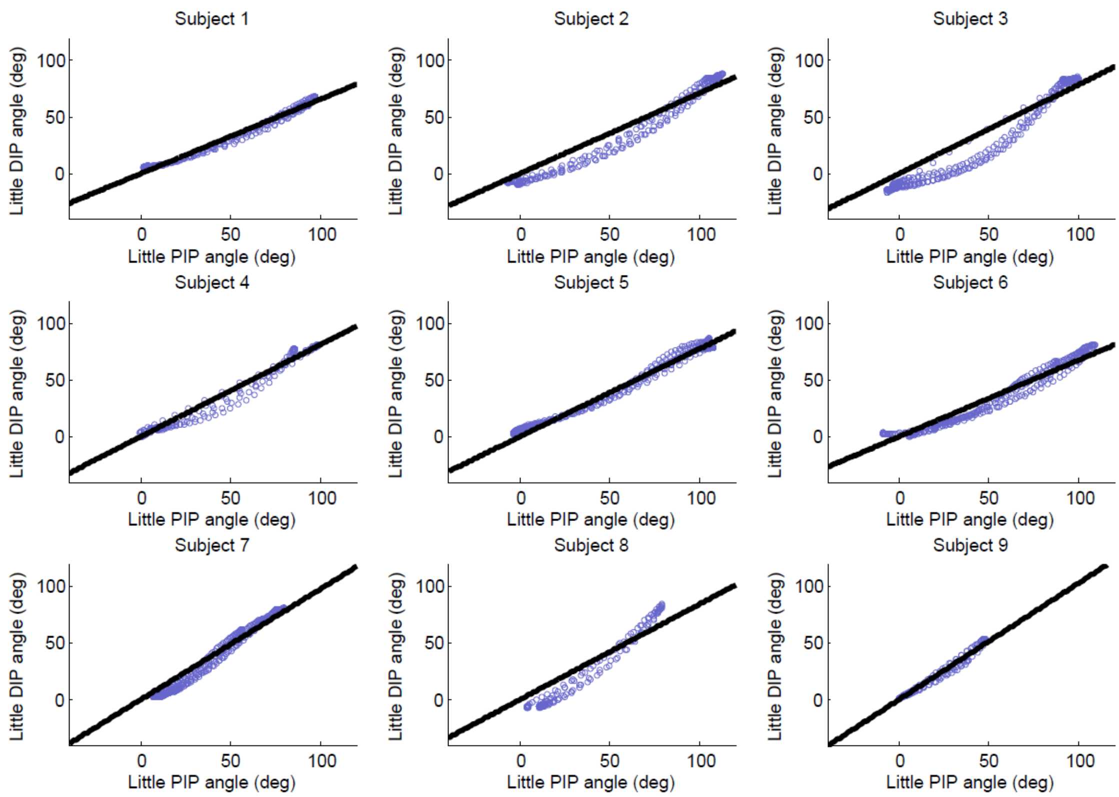


Figure AII.12: Scatter plots of little finger PIP and DIP angles recorded (in degrees) during FMT, for each subject. Regression line of each subject's data plotted in black.

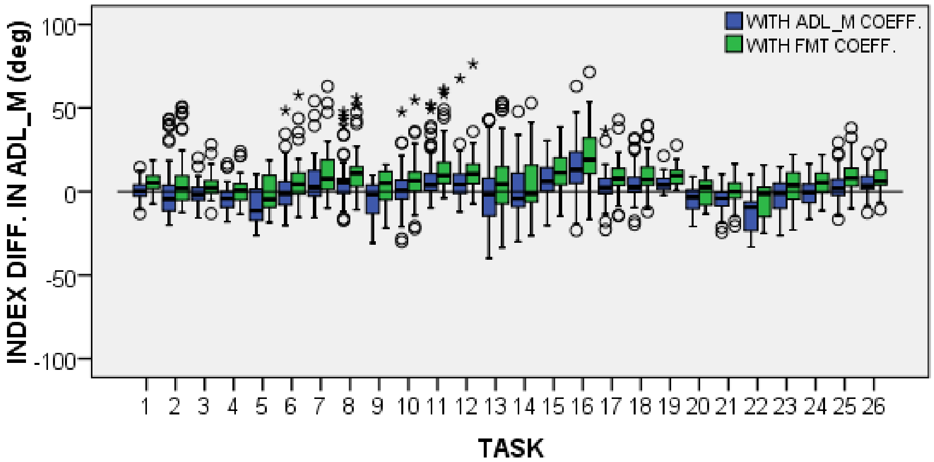


Figure AII.13: Box and whiskers plots of error (in degrees) obtained in each task during ADL_M when estimating the index DIP angle from the PIP one using the coefficients obtained during FMT (in green) and during ADL_M (in blue). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

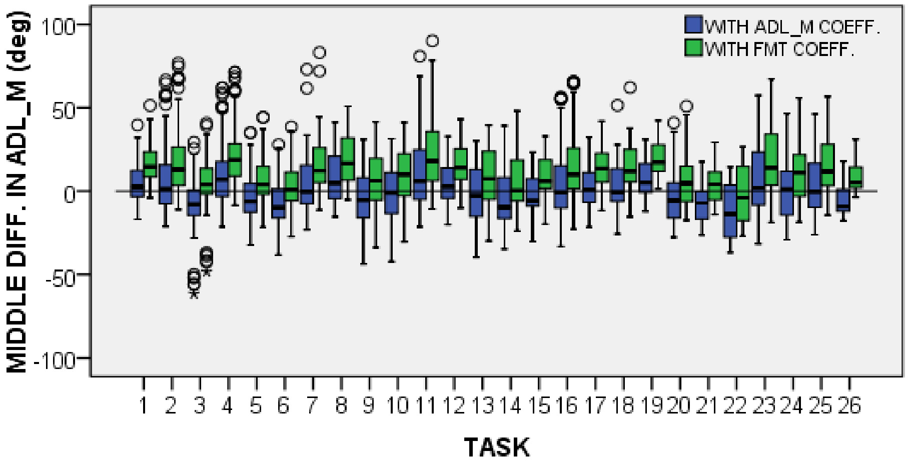


Figure AII.14: Box and whiskers plots of error (in degrees) obtained in each task during ADL_M when estimating the middle DIP angle from the PIP one using the coefficients obtained during FMT (in green) and during ADL_M (in blue). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

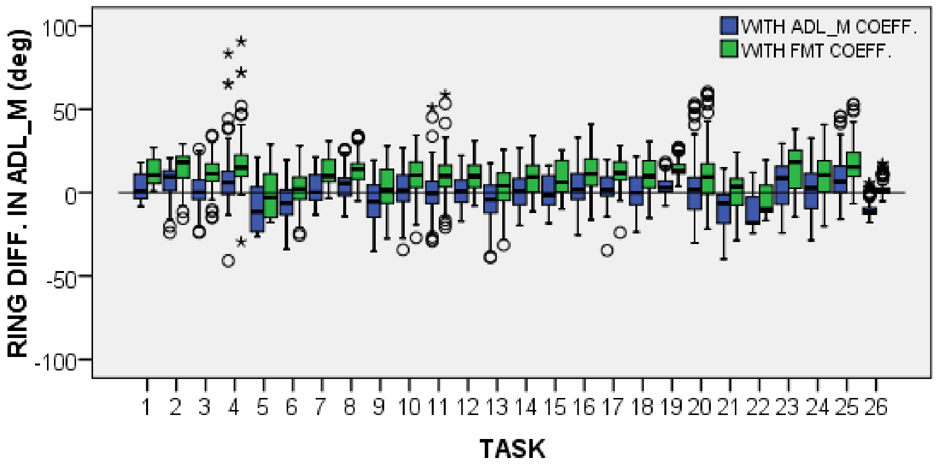


Figure AII.15: Box and whiskers plots of error (in degrees) obtained in each task during ADL_M when estimating the ring DIP angle from the PIP one using the coefficients obtained during FMT (in green) and during ADL_M (in blue). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

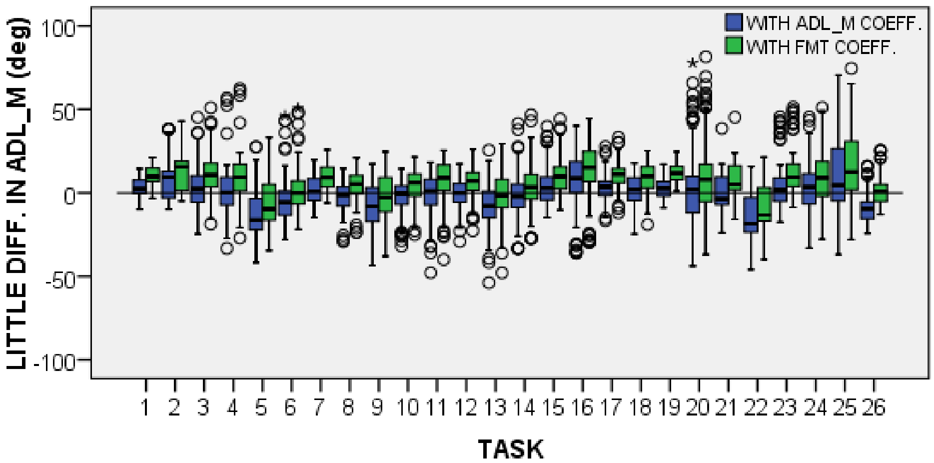


Figure AII.16: Box and whiskers plots of error (in degrees) obtained in each task during ADL_M when estimating the little DIP angle from the PIP one using the coefficients obtained during FMT (in green) and during ADL_M (in blue). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

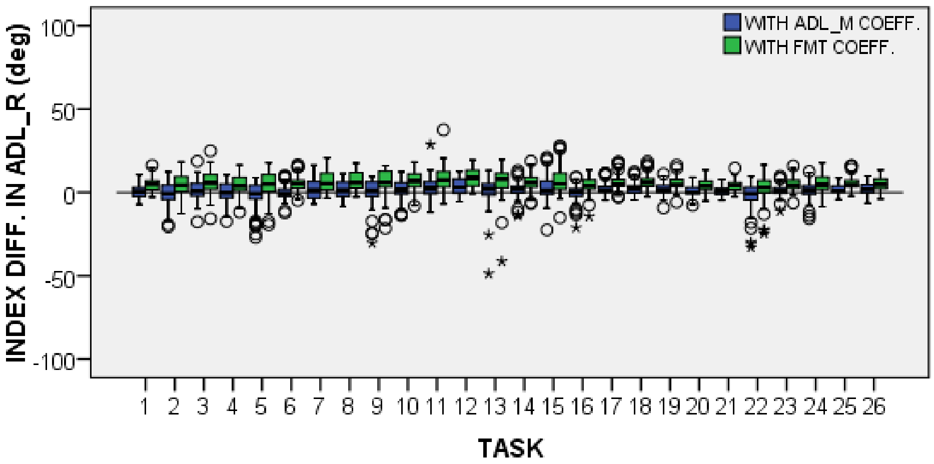


Figure AII.17: Box and whiskers plots of error (in degrees) obtained in each task during ADL_R when estimating the index DIP angle from the PIP one using the coefficients obtained during FMT (in green) and during ADL_M (in blue). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

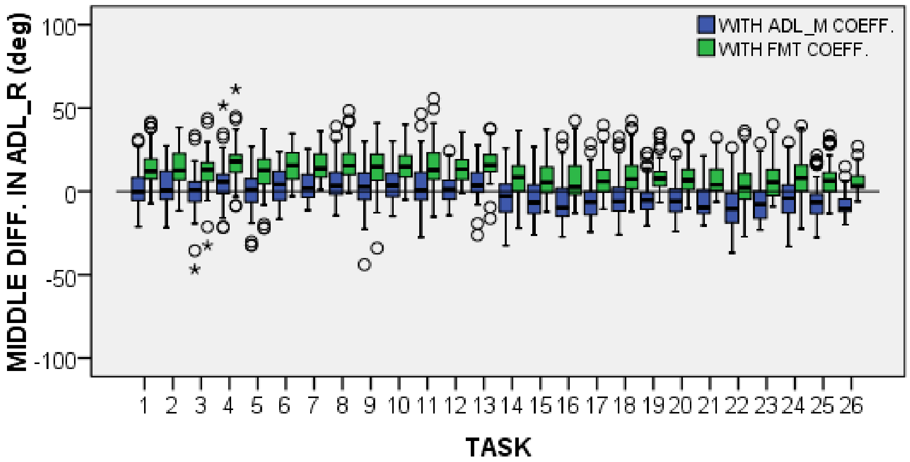


Figure AII.18: Box and whiskers plots of error (in degrees) obtained in each task during ADL_R when estimating the middle DIP angle from the PIP one using the coefficients obtained during FMT (in green) and during ADL_M (in blue). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

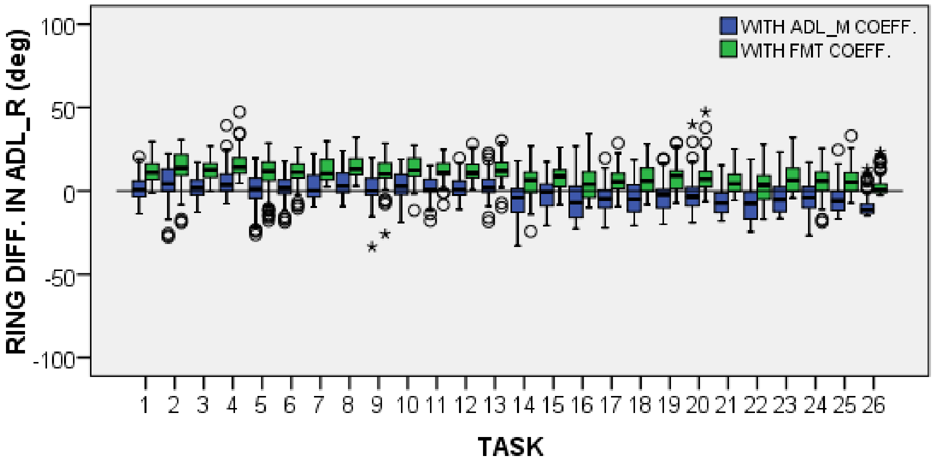


Figure AII.19: Box and whiskers plots of error (in degrees) obtained in each task during ADL_R when estimating the ring DIP angle from the PIP one using the coefficients obtained during FMT (in green) and during ADL_M (in blue). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

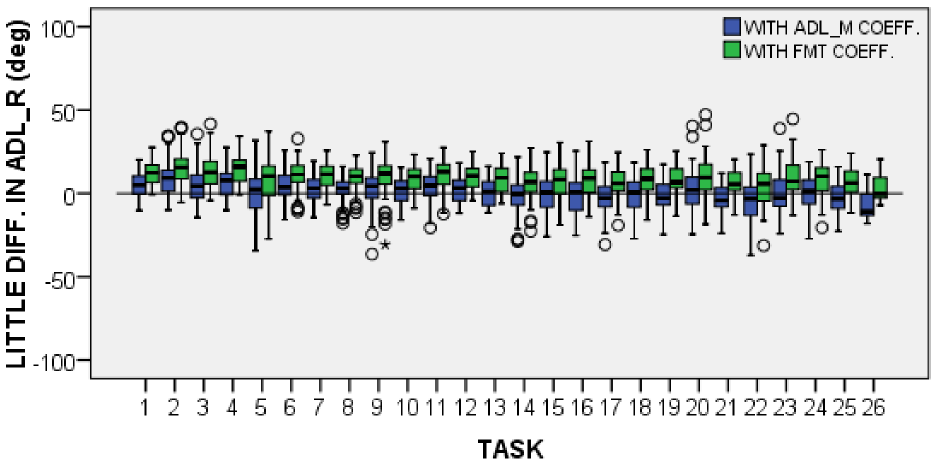


Figure AII.20: Box and whiskers plots of error (in degrees) obtained in each task during ADL_R when estimating the little DIP angle from the PIP one using the coefficients obtained during FMT (in green) and during ADL_M (in blue). Tasks #1 to #26 (ADLs performance) labeled as in Table 3.4.2.

Appendix III

This appendix contains the document "A guide to the interpretation of the KINE-ADL BE-UJI Dataset", provided along with the main dataset. This document is key to understand the nature of the data provided, detailing aspects such as the acquisition protocol, data series, anatomical angles, tasks performed, objects used or scenarios, among other key data.

A guide to the interpretation of the KINE-ADL BE-UJI dataset

March 2019

Biomechanics and Ergonomics Research Group

Universitat Jaume I (Spain)

Index

Key data

- **Research group:** BE-UJI
- **Data type:** Motion data, hand postures
- **Hand type:** Human hand
- **Hand recorded:** Right and left
- **Data structure:** Joint angles (deg)
- **Data format:** Matlab structure (.mat)
- **Sampling rate**: 100Hz
- **Action type:** Feeding and cooking activities of daily living
- **Kin. Model #DoF**: 18
- **Equipment:** Motion capture system (CyberGlove)
- **Number of subjects:** 20
- **Number of tasks:** 178
- **Objects type**: Real objects
- **Data filtering**: Low pass 2nd order two-way Butterworth filter, cut-off freq. 10Hz
- **Year**: 2017
- **Additional data:** Age, gender, laterality, weight, height, hand length, hand width and measured AROM of the subjects recruited.

  Contact:
  Alba Roda-Sales: rodaa@uji.es
  Margarita Vergara: vergara@uji.es
  Joaquín L. Sancho-Bru: sancho@uji.es

AIII.1 Introduction

This document is a guide to the interpretation of the KINE-ADL BE-UJI DATASET. This dataset is the result of recording the kinematics of the hands of 20 subjects while performing feeding and cooking activities of daily living, with a total of 58 records per subject (7h, 30min 43s of recordings throughout the whole experiment). These activities were carried out with real objects that are representative of the most commonly used ones, based on those proposed in the YCB Set.

The parameters related to the acquisition, processing and presentation of the data are detailed in the following sections of the document. All the recorded activities are explained in detail, as well as the environment and the objects used to carry them out.

AIII.2 Experiment

Equipment

Data acquisition was performed using two CyberGlove instrumented gloves (CyberGlove II on the right hand and CyberGlove III on the left hand). Each of these gloves has 18 strain gauges that allow the anatomical angles of the underlying joints to be determined.

A 0-255 signal is obtained from each gauge. The angle rotated by each joint with respect to the reference posture (Figure AIII.1) is then calculated from these signals, according to the calibration protocol proposed in [23]. This protocol includes the determination of gains and also some corrections because of cross-coupling effects for specific anatomical angles.

Figure AIII.1: Reference posture (hands resting flat on the table, with the fingers and thumb close together, and with the middle fingers aligned with the forearms.

The anatomical angles obtained according to protocol [1] are those shown in Figure AIII.2:

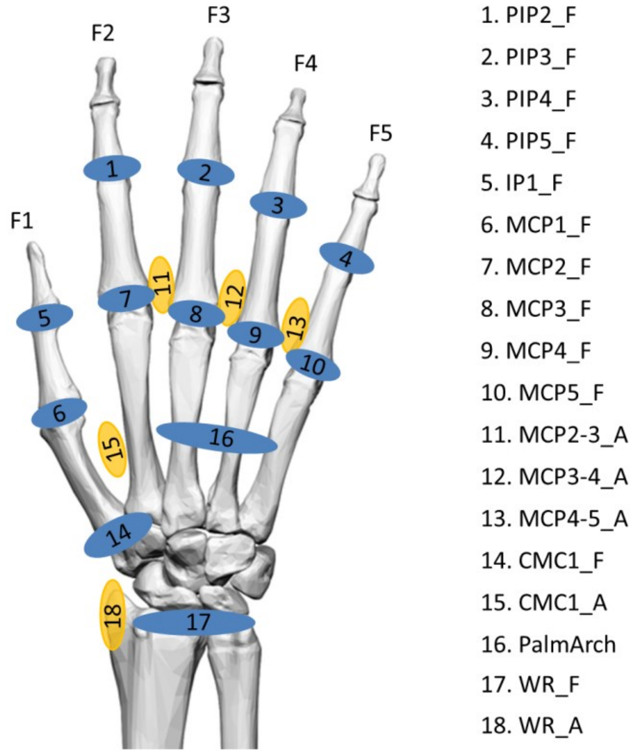


Figure AIII.2: Nomenclature: _F for flexion (in blue), _A for abduction (in yellow); 1 to 5, digits. Joints: IP for interphalangeal joint, PIP for proximal interphalangeal joints, MCP for metacarpophalangeal joints, CMC for carpometacarpal joints, PalmArch for palmar arch, WR for wrist.

Data acquisition

CyberGlove data for the reference posture and the movements during the performance of the different tasks were acquired at 100Hz for each subject.

Study participants

The study consisted of two experiments (A and B), with 20 subjects (10 males, 10 females) participating in each experiment. Only 15 subjects participated in both experiments, so that the total amount of subjects recruited was 25. In both experiments, two of the subjects were left-handed. The mean age of subjects recruited was 35.5±7.67 years in experiment A and 38.05±9.52 years in experiment B. The criteria used to select subjects were gender parity in overall data, age between 20 and 65, no reported upper limb pathologies and laterality representative of the overall population (20% of data from left-handed individuals). Before the experiments, all participants gave their written informed consent. All the experiments were performed in accordance with the Ethics Committee of the Universitat Jaume I.

Environment

The tasks were performed in the laboratory, within an environment that simulated a kitchen. The scenario was composed of: a refrigerator (Scenario 1) (Figure AIII.3), a high cabinet (Scenario 2) (Figure AIII.4), shelves (Scenario 3) (Figure AIII.5, Figure AIII.6), a small worktop (Scenario 4) (Figure AIII.7), a sink and a rubbish bin (Scenario 5) (Figure AIII.8), a large worktop (Scenario 6) (Figure AIII.9), a low cabinet with a drawer in its upper part (Figure AIII.3) and shelves in the lower part, which has a door (Scenario 7) (Figure AIII.10), a table and a chair (Figure AIII.11) (Figure AIII.12) and an oven (Scenario 9) (Figure AIII.13).

Figure AIII.3: Fridge (Scenario 1)

Figure AIII.4: High cabinet (Scenario 2)

Figure AIII.5: Shelves (Scenario 3)

Figure AIII.6: Close-up of the shelves (Scenario 3)

Figure AIII.7: Small worktop (Scenario 4)

Figure AIII.8: Sink and rubbish bin (Scenario 5)

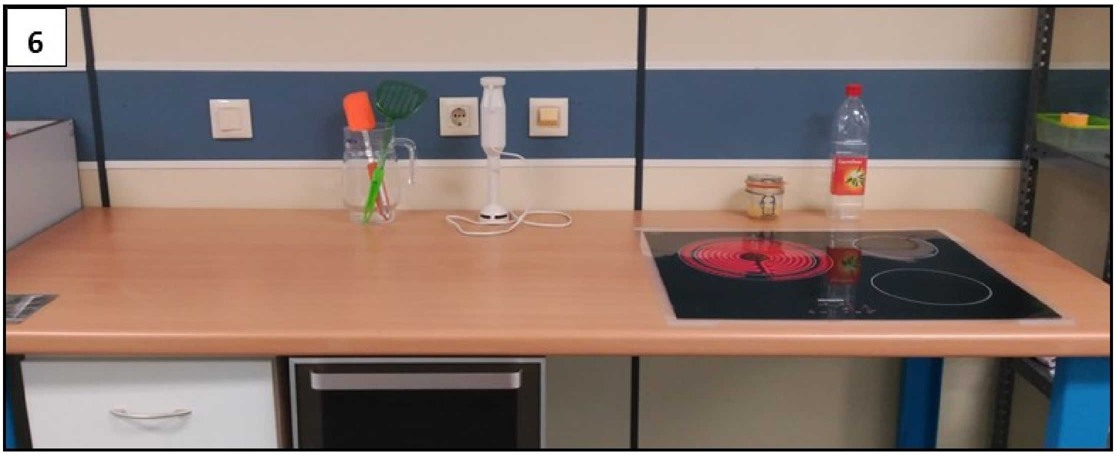


Figure AIII.9: Large worktop (Scenario 6)

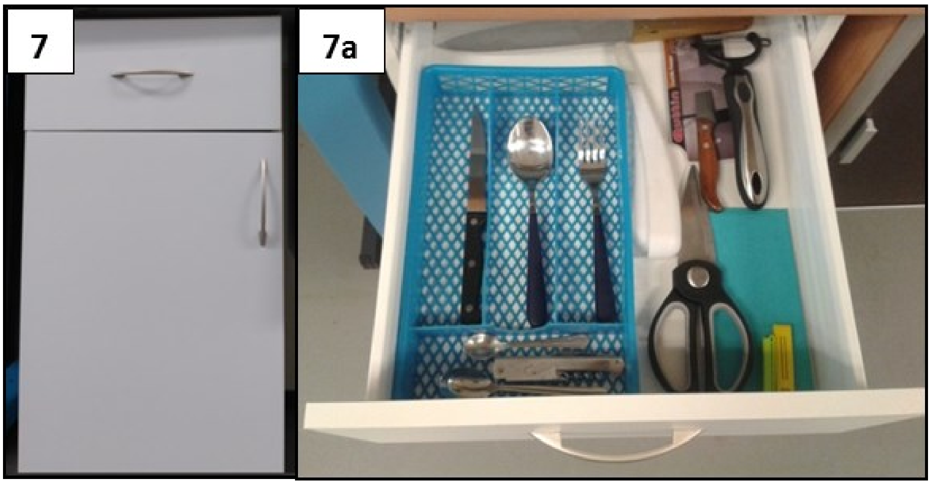


Figure AIII.10: Cabinet with drawer in its upper part (Scenario 7a)

Figure AIII.11: Cabinet with a door and shelves in its lower part (Scenario 7b).

Figure AIII.12: Table with chair (Scenario 8).

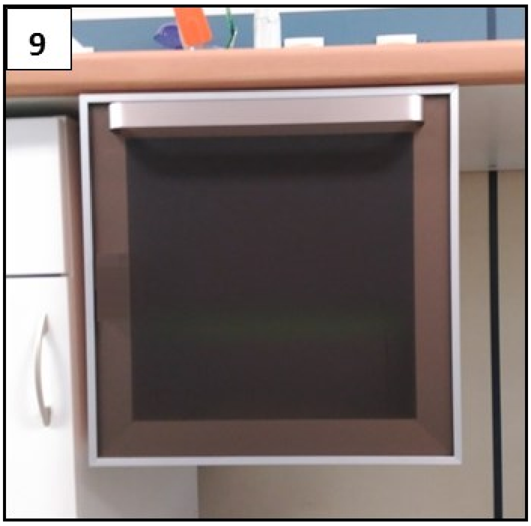


Figure AIII.13: Oven (Scenario 9).

Objects

The 66 objects used in the recorded tasks, together with their main characteristics, are detailed in Appendix III.A. Some of the objects were not real, in order to prevent the gloves from getting stained or wet. For example, in the task of breaking eggs, the eggs were previously emptied through a small hole made in the shell. All liquids were replaced by water, and materials such as flour or sugar that could have stained the gloves were replaced by durum wheat semolina. Pieces of polystyrene or cardboard were used to simulate biscuits, bread or crisps. The location of the objects in each scenario was as shown in Figure AIII.3 to Figure AIII.13 with the exceptions detailed in the tables in Appendix III.B for each task.

Recorded tasks

Two experiments (A and B) were performed. In experiment A, the activities performed were: having breakfast (preparing and having it), preparing a cake and preparing omelettes. In experiment B, the activities were: setting the table, cleaning the table and washing the dishes, making coffee and preparing a simple meal. The recording of these activities was divided into 33 recordings (R) in experiment A and 25 in experiment B. These recordings can be seen in the following tables, where a registration number (R) was assigned so that the one-hundred ones (100 onwards) belong to experiment A, while the two-hundred ones belong to experiment B. Some of the records were performed with the subject standing and others while sitting on a chair (specified in the table with an "S" if sitting). Furthermore, the scenario where the tasks were performed is specified (as "SC."), as well as the objects used (specified as "OBJ."). All the eating or drinking activities were simulated, by just bringing the food closer to the mouth, and this has been indicated in the task description.

Recordings of experiment A are presented in Table AIII.1.

Table III.1: Recordings in experiment A.

R	OBJ.	SC.	S	PREPARING AND HAVING BREAKFAST
101	6, 38, 40, 41, 62	2, 3a, 4		Using a toaster.
102	6, 40, 41, 62	4, 8		Setting the table: placing the toast.
103	42, 51, 60	1, 3a, 8		Setting the table: placing a box of biscuits, a carton of milk and an apple.
104	10, 11, 50, 55	1, 2, 8		Setting the table: placing a jar of jam, a tub of butter, a mug and a glass.
105	3, 4	7a, 8		Setting the table: placing a spoon and a knife and sitting on the chair.
106	11, 51	8	x	Pouring and drinking milk.
107	11, 42, 66	8	x	Dipping a biscuit in milk and eating it.
108	10, 57	8	x	Pouring and drinking juice.
109	3, 41, 50	8	x	Spreading butter on toast.
110	4, 41, 55	8	x	Spreading jam on toast and eating it.
111	60	8	x	Eating (simulated) the apple.
R	**OBJ.**	**SC.**	**S**	**PREPARING, BAKING AND EATING A CAKE**
112	8, 53, 61	1, 2, 6		Carrying utensils and ingredients to the worktop: a bowl, a carton of eggs and a lemon.
113	43, 44, 46	3a, 6		Carrying ingredients to the worktop: a jar with flour in it, a bag of sugar and a box of baking powder.
114	10, 52	1, 2, 6		Carrying utensils and ingredients to the worktop: a carton of milk and a glass.
115	8, 53, 54	5, 6		Breaking an egg into a bowl and throwing the eggshell into the bin.
116	2, 8	6, 7a		Beating the egg with a fork.
117	10, 43	6		Filling a glass with sugar.

118	23, 61	3b, 6		Grating a lemon.
119	1, 10, 44	6, 7a		Filling a glass with flour.
120	8, 10, 19, 52	6, 7a		Opening a carton of milk with scissors and pouring milk.
121	46	6		Pouring baking powder into the bowl.
122	8, 39	6		Using a mixer to mix the ingredients for the cake dough.
123	8, 17, 28	3b, 6		Pouring the cake dough onto the baking tray and using a spatula.
124	28	6, 9		Putting the baking tray into the oven. Taking the baking tray out of the oven.
125	3, 26, 28	6, 7a		Cutting a piece of cake with a knife and eating it (simulated).
126	52, 53, 61	1, 6		Putting the spatula, the knife, the bowl, the glass and the grater in the sink.
127	52, 53, 61	1, 6		Carrying the carton of eggs, the lemon and the carton of milk back to the fridge.
128	43, 44, 46	3a, 6		Carrying the jar of flour, the bag of sugar and the baking powder to the shelves.
129	29	6, 9		Putting the tray with 3kg of food on it into the oven. Taking the tray out of the oven.
R	**OBJ.**	**SC.**	**S**	**PREPARING OMELETTES**
130	2, 8, 56	6		Beating an egg and salting it.
131	14, 15, 58	3b, 6		Preparing the pan for cooking on the hob.
132	2, 8, 14, 16	6		Cooking and serving a small omelette.
133	3, 6, 14, 15	6		Cooking, serving and cutting a big omelette.

Recordings in experiment B are presented in Table AIII.2:

Table AIII.2: Recordings in experiment B.

R	OBJ.	SC.	S	SETTING THE TABLE
201	32	7b, 8		Putting a tablecloth on the table.
202	2, 3, 6, 10, 31	2, 7a, 8		Placing a dish, a glass, a fork, a knife and a napkin.
203	8, 21, 22, 30	1, 3a, 8		Placing a jug of water, an oil cruet, a salt-shaker and a bowl.
R	**OBJ.**	**SC.**	**S**	**CLEARING THE TABLE AND WASHING THE DISHES**
204	10, 21, 22, 30	1, 3a, 5, 8		Putting the glass, the jug, the oil cruet and the salt-shaker back in their place.
205	3, 6	5, 8		Throwing the leftovers on the plates into the rubbish bin.
206	2, 8	5, 8		Throwing the leftovers in the bowls into the rubbish bin.
207	32	7b, 8		Removing the tablecloth from the table and folding it.
208	2, 3, 6, 8, 10, 34, 36	4, 5		Washing the glass, the bowl, the dish, the fork and the knife.
209	2, 3, 6, 8, 10, 33	2, 4, 7a		Putting the glass, the bowl, the dish, the fork and the knife back in their place.
210	33, 35	5, 6		Cleaning the worktop.
R	**OBJ.**	**SC.**	**S**	**PREPARING AND DRINKING COFFEE**
211	45	3a, 4		Taking a jar of ground coffee and opening it.
212	4, 37, 45	4		Filling the filter handle of the coffee machine with coffee.
213	12, 37, 45	2, 3a, 4		Placing a cup under the coffee machine and pressing the power button.
214	12, 20, 24	3a, 3b, 4, 8		Placing the cup of coffee and the sugar pot on a tray. Carrying it to the table.
215	37	4, 5		Throwing the used ground coffee into the rubbish bin.
216	5, 12, 24, 25	8	x	Adding sugar to the coffee, stirring and drinking it (simulated).
R	**OBJ.**	**SC.**	**S**	**PREPARING AND EATING A SIMPLE MEAL**
217	8, 26, 49	3b, 6		Pouring crisps from a bag into a bowl.
218	49, 63	6, 7a		Closing the bag of crisps with a sealing clip.
219	9, 48	3a, 5, 6		Pouring olives from a tin into a little bowl.
220	47	3a, 6		Pouring salted biscuits from a jar onto a dish.
221	6, 8, 9	6, 8		Setting the table: placing the dish and the bowls.
222	18, 59	3b, 8		Opening a bottle of wine with a corkscrew.
223	13	2, 8		Setting the table: placing a glass of wine. Sitting on the chair.
224	13, 59	8	x	Pouring wine and drinking it (simulated).
225	26, 64, 65	8	x	Eating (simulated) olives, crisps and biscuits.

Each of these records (R) is composed of different elementary tasks or parts, which are detailed in Appendix III.B. For example, in the activity of having breakfast (with 11 records, as seen in Table AIII.1) record R=106 is composed of 4 elementary tasks: opening the carton, pouring, closing the carton and drinking (see Table AIII.3). For an unambiguous identification of each of the tasks, a unique ID was assigned for each elementary task, with a total of 99 elementary tasks in experiment A and 79 in B. In Appendix III.B, the object/s used in each of the tasks are also specified. All the elementary tasks involved grasping or manipulating a product or element with the hands, except for some cases where the subject moved without handling anything, which were labelled as “Displacement without manipulation”. For each elementary task, the record considers all time instants since the object was grasped until it was released. In those cases in which the object was released in a specific place or transported to a specific part of the scenario, this place is specified in the description of the elementary task. In all other cases, the release was performed on the closest surface to the subject (table, worktop, etc.).

Table AIII.3 Elementary tasks into which task n°106 is divided.

R	ID	OBJ.	SC.	S	HAVING BREAKFAST
106	16	51	8	x	Opening the cap of the carton of milk
	17	11, 51	8	x	Pouring milk into the mug from the carton
	18	51	8	x	Closing the carton of milk
	19	11	8	x	Drinking from the mug (simulated)

AIII.3 Data processing

The raw data collected from the CyberGlove gloves were processed with Matlab to obtain the parameters corresponding to each joint based on the gains and corrections calculated for each of the gauges, according to the protocol presented in [1]. After that, the initial and final instants of each record, in which the hands were static, were removed. The records were then separated into the different elementary tasks as detailed in Appendix II. Finally, the data were filtered with a 2nd order two-way low pass Butterworth filter with a cut-off frequency of 10Hz.

AIII.4 Data files

Filenames

Data is presented as a single Matlab data structure (BE_UJI_DATASET.mat), which is composed of two secondary structures (KINEMATIC_DATA and SUBJECT_DATA). KINEMATIC_DATA contains all kinematic data recorded, classified by experiment, record, part and subject, while SUBJECT_DATA contains data of the subjects recruited (age, gender, laterality, weight, height, hand length, hand width and measured AROM).

Data series

The fields contained in both substructures are those detailed in the following schemes:

KINEMATIC DATA

▪ EXPERIMENT	*ID of the experiment.*		
▪ SUBJECT	*ID of the subject.*		
▪ RECORD (R)	*ID of the recording.*		
▪ ID	*ID of the task.*		
▪ ANGLES		▪ **Time**	*Time stamp*
		▪ **R_CMC1_F**	*Flexion of carpometacarpal 1 (Right hand)*
		▪ **R_CMC1_A**	*Abduction of carpometacarpal 1 (Right hand)*
		▪ **R_MCP1_F**	*Flexion of metacarpophalangeal 1 (Right hand)*
		▪ **R_IP1_F**	*Flexion of interphalangeal 1 (Right hand)*
		▪ **R_MCP2_F**	*Flexion of metacarpophalangeal 2 (Right hand)*
		▪ **R_MCP2-3_A**	*Relative Abduction of metacarpophalangeal 2 and 3 (Right hand)*
		▪ **R_PIP2_F**	*Flexion of proximal interphalangeal 2 (Right hand)*
		▪ **R_MCP3_F**	*Flexion of metacarpophalangeal 3 (Right hand)*
		▪ **R_PIP3_F**	*Flexion of proximal interphalangeal 3 (Right hand)*
		▪ **R_MCP4_F**	*Flexion of metacarpophalangeal 4 (Right hand)*
		▪ **R_MCP3-4_A**	*Relative Abduction of metacarpophalangeal 3 and 4 (Right hand)*
		▪ **R_PIP4_F**	*Flexion of proximal interphalangeal 4 (Right hand)*
		▪ **R_PalmArch**	*Palmar Arch (Right hand)*
		▪ **R_MCP5_F**	*Flexion of metacarpophalangeal 5 (Right hand)*
		▪ **R_MCP4-5_A**	*Relative Abduction of metacarpophalangeal 4 and 5 (Right hand)*
		▪ **R_PIP5_F**	*Flexion of proximal interphalangeal 5 (Right hand)*
		▪ **R_WR_F**	*Flexion of wrist (Right hand)*
		▪ **R_WR_A**	*Abduction of wrist (Right hand)*
		▪ **L_CMC1_F**	*Flexion of carpometacarpal 1 (Left hand)*
		▪ **L_CMC1_A**	*Abduction of carpometacarpal 1 (Left hand)*
		▪ **L_MCP1_F**	*Flexion of metacarpophalangeal 1 (Left hand)*
		▪ **L_IP1_F**	*Flexion of interphalangeal 1 (Left hand)*
		▪ **L_MCP2_F**	*Flexion of metacarpophalangeal 2 (Left hand)*
		▪ **L_MCP2-3_A**	*Relative Abduction of metacarpophalangeal 2 and 3 (Left hand)*
		▪ **L_PIP2_F**	*Flexion of proximal interphalangeal 2 (Left hand)*
		▪ **L_MCP3_F**	*Flexion of metacarpophalangeal 3 (Left hand)*
		▪ **L_PIP3_F**	*Flexion of proximal interphalangeal 3 (Left hand)*
		▪ **L_MCP4_F**	*Flexion of metacarpophalangeal 4 (Left hand)*
		▪ **L_MCP34_A**	*Relative Abduction of metacarpophalangeal 3 and 4 (Left hand)*
		▪ **L_PIP4_F**	*Flexion of proximal interphalangeal 4 (Left hand)*
		▪ **L_PalmArch**	*Palmar Arch (Left hand)*
		▪ **L_MCP5_F**	*Flexion of metacarpophalangeal 5 (Left hand)*
		▪ **L_MCP4-5_A**	*Relative Abduction of metacarpophalangeal 4 and 5 (Left hand)*
		▪ **L_PIP5_F**	*Flexion of proximal interphalangeal 5 (Left hand)*
		▪ **L_WR_F**	*Flexion of wrist (Left hand)*
		▪ **L_WR_A**	*Abduction of wrist (Left hand)*

SUBJECT DATA

- SUBJECT — *ID of the subject.*
- GENDER — *(1=male, 2=female)*
- LATERALITY — *(1=right handed, 2=left handed)*
- AGE — *Age when experiment was performed (2017)*
- WEIGHT — *(kg)*
- HEIGHT — *(cm)*
- HL_R — *Right hand length (mm)*
- HL_L — *Left hand length (mm)*
- HW_R — *Right hand width (mm)*
- HW_L — *Left hand width (mm)*
- AROM
  - **R_CMC1_F** — *Max. Flexion of carpometacarpal 1 (Right hand)*
  - **R_CMC1_E** — *Min. Flexion (=Extension) of carpometacarpal 1 (Right hand)*
  - **R_CMC1_A** — *Max. Abduction of carpometacarpal 1 (Right hand)*
  - **R_MCP1_F** — *Max. Flexion of metacarpophalangeal 1 (Right hand)*
  - **R_MCP1_E** — *Min. Flexion (=Extension) of metacarpophalangeal 1 (Right hand)*
  - **R_IP1_F** — *Max. Flexion of interphalangeal 1 (Right hand)*
  - **R_IP1_E** — *Min. Flexion (=Extension) of interphalangeal 1 (Right hand)*
  - **R_MCP2_F** — *Max. Flexion of metacarpophalangeal 2 (Right hand)*
  - **R_MCP2_E** — *Min. Flexion (=Extension) of metacarpophalangeal 2 (Right hand)*
  - **R_MCP2-3_A** — *Max. Relative abduction of metacarpophalangeal 2 and 3 (Right hand)*
  - **R_PIP2_F** — *Max. Flexion of proximal interphalangeal 2 (Right hand)*
  - **R_PIP2_E** — *Min. Flexion (=Extension) of proximal interphalangeal 2 (Right hand)*
  - **R_MCP3_F** — *Max. Flexion of metacarpophalangeal 3 (Right hand)*
  - **R_MCP3_E** — *Min. Flexion (=Extension) of metacarpophalangeal 3 (Right hand)*
  - **R_PIP3_F** — *Max. Flexion of proximal interphalangeal 3 (Right hand)*
  - **R_PIP3_E** — *Min. Flexion (=Extension) of proximal interphalangeal 3 (Right hand)*
  - **R_MCP4_F** — *Max. Flexion of metacarpophalangeal 4 (Right hand)*
  - **R_MCP4_E** — *Min. Flexion (=Extension) of metacarpophalangeal 4 (Right hand)*
  - **R_MCP3-4_A** — *Max. Relative Abduction of metacarpophalangeal 3 and 4 (Right hand)*
  - **R_PIP4_F** — *Max. Flexion of proximal interphalangeal 4 (Right hand)*
  - **R_PIP4_E** — *Min. Flexion (=Extension) of proximal interphalangeal 4 (Right hand)*
  - **R_PalmArch** — *Max. Palmar Arch (Right hand)*
  - **R_MCP5_F** — *Max. Flexion of metacarpophalangeal 5 (Right hand)*
  - **R_MCP5_E** — *Min. Flexion (=Extension) of metacarpophalangeal 5 (Right hand)*
  - **R_MCP4-5_A** — *Max. Relative Abduction of metacarpophalangeal 4 and 5 (Right hand)*
  - **R_PIP5_F** — *Max. Flexion of proximal interphalangeal 5 (Right hand)*
  - **R_PIP5_E** — *Min. Flexion (=Extension) of proximal interphalangeal 5 (Right hand)*
  - **R_WR_F** — *Max. Flexion of wrist (Right hand)*
  - **R_WR_E** — *Min. Flexion (=Extension) of wrist (Right hand)*
  - **R_WR_UD** — *Max. Abduction (=Ulnar deviation) of wrist (Right hand)*
  - **R_WR_RD** — *Min. Abduction (=Radial deviation) of wrist (Right hand)*
  - **L_CMC1_F** — *Max. Flexion of carpometacarpal 1 (Left hand)*
  - **L_CMC1_E** — *Min. Flexion (=Extension) of carpometacarpal 1 (Left hand)*
  - **L_CMC1_A** — *Max. Abduction of carpometacarpal 1 (Left hand)*
  - **L_MCP1_F** — *Max. Flexion of metacarpophalangeal 1 (Left hand)*
  - **L_MCP1_E** — *Min. Flexion (=Extension) of metacarpophalangeal 1 (Left hand)*
  - **L_IP1_F** — *Max. Flexion of interphalangeal 1 (Left hand)*
  - **L_IP1_E** — *Min. Flexion (=Extension) of interphalangeal 1 (Left hand)*
  - **L_MCP2_F** — *Max. Flexion of metacarpophalangeal 2 (Left hand)*
  - **L_MCP2_E** — *Min. Flexion (=Extension) of metacarpophalangeal 2 (Left hand)*
  - **L_MCP2-3_A** — *Max. Relative abduction of metacarpophalangeal 2 and 3 (Left hand)*
  - **L_PIP2_F** — *Max. Flexion of proximal interphalangeal 2 (Left hand)*
  - **L_PIP2_E** — *Min. Flexion (=Extension) of proximal interphalangeal 2 (Left hand)*
  - **L_MCP3_F** — *Max. Flexion of metacarpophalangeal 3 (Left hand)*
  - **L_MCP3_E** — *Min. Flexion (=Extension) of metacarpophalangeal 3 (Left hand)*
  - **L_PIP3_F** — *Max. Flexion of proximal interphalangeal 3 (Left hand)*
  - **L_PIP3_E** — *Min. Flexion (=Extension) of proximal interphalangeal 3 (Left hand)*
  - **L_MCP4_F** — *Max. Flexion of metacarpophalangeal 4 (Left hand)*
  - **L_MCP4_E** — *Min. Flexion (=Extension) of metacarpophalangeal 4 (Left hand)*
  - **L_MCP3-4_A** — *Max. Relative Abduction of metacarpophalangeal 3 and 4 (Left hand)*
  - **L_PIP4_F** — *Max. Flexion of proximal interphalangeal 4 (Left hand)*
  - **L_PIP4_E** — *Min. Flexion (=Extension) of proximal interphalangeal 4 (Left hand)*
  - **L_PalmArch** — *Max. Palmar Arch (Left hand)*
  - **L_MCP5_F** — *Max. Flexion of metacarpophalangeal 5 (Left hand)*
  - **L_MCP5_E** — *Min. Flexion (=Extension) of metacarpophalangeal 5 (Left hand)*
  - **L_MCP4-5_A** — *Max. Relative Abduction of metacarpophalangeal 4 and 5 (Left hand)*
  - **L_PIP5_F** — *Max. Flexion of proximal interphalangeal 5 (Left hand)*
  - **L_PIP5_E** — *Min. Flexion (=Extension) of proximal interphalangeal 5 (Left hand)*
  - **L_WR_F** — *Max. Flexion of wrist (Left hand)*
  - **L_WR_E** — *Min. Flexion (=Extension) of wrist (Left hand)*
  - **L_WR_UD** — *Max. Abduction (=Ulnar deviation) of wrist (Left hand)*
  - **L_WR_RD** — *Min. Abduction (=Radial deviation) of wrist (Left hand)*

Sign criteria

- **PIP(2-5)_F, IP1_F, CMC1_F, MCP(1-5)_F, WR_F:** Flexion + / Extension -
- **MCP(2-3, 3-4, 4-5)_A**: Fingers separated + / Fingers together -
- **PalmArch:** Flexion +/Extension -
- **CMC1_F:** Flexion +/Extension - (See Figure AIII.14)
- **CMC1_A:** Abduction +/Adduction - (See Figure AIII.14)
- **WR_A:** Ulnar deviation +/Radial deviation -

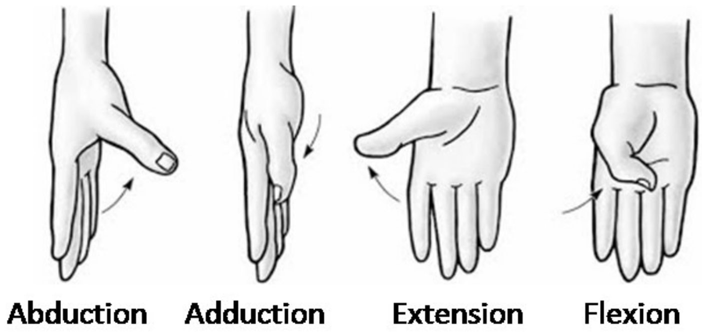
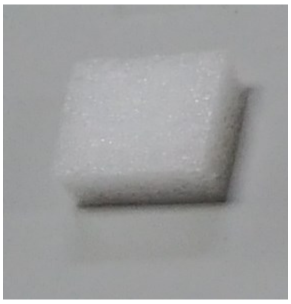


Figure AIII.14: Movements of the carpometacarpal joint.

Appendix III.A: Objects

1. Soup spoon  **Weight:** 50g **Material:** Stainless steel and plastic.	**2. Fork**  **Weight:** 40g **Material:** Stainless steel and plastic.	**3. Knife**  **Weight:** 40g **Material:** Stainless steel and plastic.
4. Dessertspoon  **Weight:** 20g **Material:** Stainless steel.	**5. Coffee spoon**  **Weight:** 15g **Material:** Stainless steel.	**6. Plate**  **Weight:** 740g **Material:** Ceramic. **Dimensions:** Ø280mm
7. Dish  **Weight:** 580g **Material:** Ceramic. **Dimensions:** Ø245mm	**8. Medium-sized bowl**  **Weight:** 600g **Material:** Glass. **Dimensions:** Ø280mm	**9. Small bowl**  **Weight:** 210g **Material:** Glass. **Dimensions:** Ø220mm
10. Glass  **Weight:** 210g **Material:** Glass. **Dimensions:** Ø76mm	**11. Mug**  **Weight:** 320g **Material:** Ceramic. **Dimensions:** Ø80mm Handle width=15mm	**12. Coffee cup**  **Weight:** 135g **Material** Ceramic. **Dimensions:** Ø62-45mm Handle width=10mm

13. Wine glass  **Weight:** 180g **Material:** Glass. **Dimensions:** Ø80mm Handle Ø=8mm	**14. Frying pan**  **Weight:** 480g **Material:** Steel and plastic. **Dimensions:** Handle thickness=35×15mm	**15. Pan lid**  **Weight:** 90g **Material:** Aluminium and plastic. **Dimensions:** Handle Ø=28mm
16. Slotted spoon  **Weight:** 60g **Material:** Plastic. **Dimensions:** Handle thickness=20×10mm	**17. Spatula**  **Weight:** 100g **Material:** Steel, aluminium and silicone. **Dimensions:** Handle thickness=30×20mm	**18. Corkscrew**  **Weight:** 70g **Material:** Stainless steel.
19. Scissors  **Weight:** 150g **Material:** Stainless steel and plastic.	**20. Tray**  **Weight:** 200g **Material:** Plastic.	**21. Oil cruet**  **Weight:** 260g **Material:** Plastic (with water as oil). **Dimensions:** Ø60mm
22. Jug of water  **Weight:** 1440g **Material:** Glass (with water). **Dimensions:** Handle thickness=10×10mm	**23. Grater**  **Weight:** 175g **Material:** Stainless steel and elastomeric plastic.	**24. Sugar pot**  **Weight:** 200g **Material:** Plastic (with durum wheat semolina as sugar). **Dimensions:** Ø85mm.

25. Sugar pot spoon  **Weight:** <10g **Material:** Plastic.	**26. Crisps**  **Weight:** <10g **Material:** Extruded polystyrene.	**27. Piece of cake**  **Weight:** <10g **Material:** Extruded polystyrene.
28. Baking tray  **Weight:** 530g **Material:** Stainless steel. Extruded polystyrene as cake.	**29. Tray with 3 kg**  **Weight:** 3030g **Material:** Stainless steel and packet of paper.	**30. Salt-shaker**  **Weight:** 250g **Material:** Glass and stainless steel (with durum wheat semolina as salt). **Dimensions:** Handle Ø=53mm.
31. Napkin  **Material:** Paper.	**32. Tablecloth**  **Weight:** 690g **Material:** Cloth.	**33. Dishcloth**  **Material:** Cloth.
34. Dish sponge  **Weight:** <10g **Material:** Sponge.	**35. Spray bottle**  **Weight:** 80g **Material:** Plastic (empty bottle).	**36. Bottle of washing-up liquid**  **Weight:** 100g **Material:** Plastic (empty bottle).

37. Coffee machine  **Weight:** 240g (handle). **Material:** Steel and plastic (handle). **Dimensions:** Handle Ø=35mm	**38. Toaster**  **Material:** Steel and plastic.	**39. Mixer**  **Weight:** 600g **Material:** Steel and plastic. **Dimensions:** Handle Ø=53mm
40. Bag of sliced bread  **Weight:** 40g (6 slices of toast + sealing clip for bags) **Material:** Plastic.	**41. Sliced bread for toast**  **Weight:** 5g per slice of toast. **Material:** Extruded polystyrene.	**42. Box of biscuits with tray inside**  **Weight** 90g **Material:** Cardboard (box and biscuits) and plastic (tray).
43. Bag of sugar and sealing clip  **Weight:** 200g **Material:** Paper and wooden sealing clip (with durum wheat semolina as sugar).	**44. Jar with flour**  **Weight:** 1000g **Material:** Plastic (with durum wheat semolina as flour). **Dimensions:** Ø120mm	**45. Jar of ground coffee**  **Weight:** 300g **Material:** Glass and plastic. Durum wheat semolina as café. **Dimensions:** Lid Ø=67mm.

46. Box with baking powder  **Weight:** 20g (with 1 bag) **Material:** Paper and cardboard. Durum wheat semolina as baking powder.	**47. Jar of salted biscuits**  **Weight:** 340g **Material:** Plastic, cardboard (biscuits) and sand (to add weight). **Dimensions:** 95×95mm	**48. Tin of olives**  **Weight:** 180g **Material:** Tin and dried chickpeas as olives. **Dimensions:** Ø60mm-Ø75mm (several tin models)
49. Bag of crisps  **Weight:** 55g **Material:** Plastic. Extruded polystyrene as crisps.	**50. Tub of butter**  **Weight:** 140g **Material:** Plastic. Clay as butter.	**51. Carton of milk (with cap)**  **Weight:** 700g **Material:** Cardboard and plastic. Water as milk. **Dimensions:** 230×70×70mm Cap Ø=30mm
52. Carton of milk (without cap)  **Weight:** 700g **Material:** Cardboard and plastic. Water as milk. **Dimensions:** 195×90×55mm	**53. Carton of eggs**  **Weight:** 100g (10g each egg) **Material:** Cardboard and empty eggs.	**54. Egg**  **Weight:** 10g **Material:** Empty egg.

55. Jar of jam **56.Salt container**  **Weight:** 440g. **Material:** Glass and steel. **Dimensions:** Ø75mm	**57. Bottle of juice**  **Weight** 660g **Material:** Glass and steel. Water as juice. **Dimensions:** Ø70mm Cap Ø=50mm	**58. Oil bottle**  **Weight:** 40g **Material:** Plastic. **Dimensions:** 68×68mm Cap Ø=28mm
59. Bottle of wine  **Weight:** 1120g **Material:** Glass and cork. Water as wine. **Dimensions:** Ø75mm	**60. Apple**  **Weight:** 20g **Material:** Plastic.	**61. Lemon**  **Weight:** 20g **Material:** Plastic.
62. Sealing clip for bags  **Weight:** 20g **Material:** Plastic.	**63. Sealing clip**  **Weight:** 20g **Material:** Plastic and steel.	**64. Olives**  **Weight:** <10g **Material:** Clay.
65. Salted biscuits  **Weight:** <10g **Material:** Cardboard.	**66. Biscuits**  **Weight:** <10g **Material:** Cardboard.	

Appendix III.B: Tasks

Experiment A

R	ID	OBJ.	SC.	S	PREPARING AND HAVING BREAKFAST
Additional objects in scenarios: **Scenario 8 (Table):** 57 (Bottle of juice).					
101	1	6	2, 4		Opening the cabinet to take out the plate and leaving it on the worktop. Closing the cabinet.
	2	40	3a, 4		Taking the bag of sliced bread from the shelf and leaving it on the worktop.
	3	40, 62	4		Opening the bag (initially closed with a sealing clip).
	4	38, 40, 41	4		Taking out a slice of bread, putting it into the toaster and pushing down the toaster lever.
102	5	41	4		Taking the slice of bread out of the toaster and putting it on the plate.
	6	40, 62	4		Closing the bag of bread with the clip.
	7	6	4, 8		Carrying the plate from the worktop to the table.
103	8	42	3a, 8		Taking the box of biscuits from the shelf and carrying it to the table.
	9	-	-		*****Displacement without manipulation.
	10	51,60	1, 8		Opening the fridge, taking out a carton of milk and the apple, closing the fridge and carrying the objects to the table.
104	11	55, 50	1, 8		Opening the fridge, taking out the jar of jam and the tub of butter, closing the fridge and carrying the objects to the table.
	12	10, 11	2, 8		Opening the cabinet, taking out the mug and the glass. Closing the cabinet and carrying the objects to the table.
105	13	-	7a		Opening the drawer.
	14	3, 4	7a, 8		Taking a dessertspoon and a knife from the drawer. Closing the drawer. Carrying the objects to the table.
	15	-	8		Pulling the chair from under the table and sitting on the chair
106	16	51	8	x	Opening the cap of the carton of milk.
	17	11, 51	8	x	Pouring milk from the carton into the mug.
	18	51	8	x	Closing the carton of milk.
	19	11	8	x	Drinking from the mug (simulated).
107	20	42	8	x	Opening a box of biscuits and taking out the plastic tray.
	21	11, 42, 66	8	x	Taking out a biscuit, dipping it in the milk and eating the biscuit (simulated).
	22	42	8	x	Pushing the tray back inside the box and closing the box.
108	23	57	8	x	Opening the bottle of juice.
	24	10, 57	8	x	Pouring juice from the bottle into the glass.
	25	57	8	x	Closing the bottle.
	26	10	8	x	Drinking from the glass (simulated).
109	27	50	8	x	Opening the tub of butter.
	28	3, 41, 50	8	x	Taking the knife and spreading butter on the slice of bread. Leaving the slice on the plate.
	29	50	8	x	Closing the butter container.
	30	55	8	x	Opening the jar of jam.

110	31	4, 41, 55	8	x	Taking the dessertspoon and spreading jam on the slice of bread. Leaving the slice on the plate.
	32	55	8	x	Closing the jar of jam.
	33	41	8	x	Taking the slice of bread from the plate and biting it (simulated). Leaving it on the plate.
111	34	60	8	x	Taking the apple, biting it twice (simulated), leaving it on the plate.
R	**ID**	**OBJ.**	**SC.**	**S**	**PREPARING, BAKING AND EATING A CAKE**
112	35	8	2, 6		Opening the kitchen cabinet, taking a bowl out, closing the cabinet and leaving the bowl on the worktop.
	36	-	-		*****Displacement without manipulation.
	37	53, 61	1, 6		Opening the fridge. Taking out a carton of eggs and a lemon. Closing the fridge. Carrying the objects to the worktop.
113	38	44	3a, 6		Taking a jar of flour from a shelf and carrying it to the worktop.
	39	-	-		*****Displacement without manipulation.
	40	43, 46	3a, 6		Taking a bag of sugar and a box of baking powder from a shelf, and carrying them to the worktop.
114	41	52	1, 6		Opening the fridge. Taking out a carton of milk, closing the fridge and carrying the milk to the worktop.
	42	-	-		*****Displacement without manipulation.
	43	10	2, 6		Opening the kitchen cabinet, taking out a glass, closing the cabinet and carrying the glass to the worktop.
115	44	53	6		Opening the carton of eggs.
	45	8, 54	6		Breaking an egg into the bowl.
	46	54	5, 6		Throwing the eggshell into the rubbish bin.
	47	53	6		Closing the carton of eggs.
116	48	2	7a		Opening a drawer, taking out a fork and closing the drawer.
	49	2, 8	6		Beating the egg with the fork.
117	50	43	6		Opening the bag of sugar (initially closed with a peg).
	51	10, 43	6		Taking the bag of sugar and filling the glass with sugar.
	52	43	6		Closing the bag of sugar with the peg.
118	53	23	3b, 6		Taking a grater from a shelf and carrying it to the worktop.
	54	23, 61	6		Taking the lemon and the grater and grating the lemon into the bowl.
119	55	44	6		Opening the jar of flour.
	56	10, 44	6		Taking the jar of flour and filling the glass with flour.
	57	1, 10, 44	7a, 6		Opening the drawer, taking out a spoon, closing the drawer. Taking two or three tablespoons of flour from the jar and pouring them into the glass.
	58	44	6		Closing the jar of flour.
120	59	19	7a, 6		Opening the drawer and taking out a pair of scissors. Leaving them on the worktop. Closing the drawer.
	60	19, 52	6		Taking the scissors to open the carton of milk and leaving them on the worktop.
	61	10, 52	6		Taking the carton of milk and pouring milk into the glass.
	62	8, 10	6		Taking the glass of milk and pouring it into the bowl.

121	63	46	6		Opening the box of baking powder, taking out one sachet and opening it. Pouring the powder into the bowl. Closing the box.
122	64	39	6		Taking the mixer from the worktop. Plugging it into a socket (with just one hand).
	65	8, 39	6		Using the mixer to mix the ingredients in the bowl.
	66	8, 39	6		Taking the mixer out of the bowl and leaving it on the worktop.
	67	39	6		Disconnecting the mixer from the socket (with just one hand).
123	68	28	3b, 6		Taking a baking tray from the shelf and carrying it to the worktop.
	69	17	6		Picking up a spatula from a pot placed on the worktop.
	70	8, 17	6		Pouring the cake dough onto the tray from the bowl using a spatula to scrape out all the dough.
	71	17, 28	6		Spreading the cake dough on the tray with the spatula and leaving the spatula inside the bowl.
124	72	28	6, 9		Opening the oven, taking the tray from the worktop, putting it into the oven and closing it.
	73	28	6, 9		Opening the oven, taking the tray out, leaving the tray on the kitchen worktop and closing the oven.
125	74	3	7a		Opening the drawer, taking out a knife and closing the drawer.
	75	3, 28	6		Cutting a piece of cake with the knife. Leaving the knife on the worktop.
	76	28, 26	6		Taking a piece of cake and biting it. Leaving the piece of cake on the worktop.
126	77	3, 8, 17	5, 6		Taking the spatula, the knife and the bowl from the worktop and putting them in the sink.
	78	-	-		*****Displacement without manipulation.
	79	10, 23	5, 6		Taking the glass and the grater from the worktop, putting them in the sink.
127	80	53, 61	1, 6		Taking the carton of eggs and the lemon from the worktop, carrying them to the fridge, opening the fridge and putting the objects inside it. Closing the fridge.
	81	-	-		*****Displacement without manipulation.
	82	52	1, 6		Taking the carton of milk from the worktop, carrying it to the fridge, opening the fridge and putting the carton inside it. Closing the fridge.
128	83	44	3a, 6		Taking the jar of flour from the worktop, carrying it to the shelf. Leaving the jar on the shelf.
	84	-	-		*****Displacement without manipulation.
	85	43, 46	3a, 6		Taking the bag of sugar and the box of baking powder from the worktop, carrying them to the shelf. Leaving the objects on the shelf.
129	86	29	6, 9		Opening the oven, taking the tray with a 3kg weight on it from the worktop, putting it into the oven and closing it.
	87	29	6, 9		Opening the oven, taking out a tray with a 3kg weight on it, leaving the tray on the worktop, closing the oven.
R	**ID**	**OBJ.**	**SC.**	**S**	**PREPARING OMELETTES**

<u>Additional objects in scenarios:</u>
Scenario 6 (Worktop): 2 (Fork), 3 (Knife), 6 (Plate), 8 (Medium-sized bowl).

130	88	2, 8	6		Taking a fork from the worktop and beating eggs (simulated) in a bowl. Leaving the fork in the bowl.
	89	8, 56	6		Opening the salt container (placed on the worktop), taking salt with the tips of the fingers and pouring it into the bowl.
131	90	14, 15	3b, 6		Taking the frying pan and its lid from a shelf and carrying them to the hob.
	91	58	6		Taking a bottle of oil from the worktop, opening the cap, pouring oil into the pan, closing the bottle and leaving the bottle on the worktop.
	92	-	6		Switching the hob on.
132	93	2, 8	6		Pouring the beaten eggs from the bowl into the pan, with the help of the fork.
	94	14, 16	6		Picking a slotted spoon from a pot on the worktop and stirring the contents of the pan.
	95	14, 16	6		Taking the omelette out of the pan with the slotted spoon and placing it on a plate. Leaving the spoon on the worktop.
133	96	14, 15	6		Taking the pan lid from the worktop, putting it over the pan and turning the omelette over with the lid.
	97	14	6		Grasping the handle of the pan and shaking it.
	98	14, 6	6		Taking the pan by the handle and putting the omelette on the plate.
	99	3, 6	6		Taking the knife from the worktop. Cutting the omelette in four pieces. Leaving the knife on the worktop.

Experiment B

R	ID	OBJ.	SC.	S	SETTING THE TABLE
<u>Additional objects in scenarios:</u> **Scenario 1 (Fridge):** 8 (Medium-sized bowl).					
201	1	32	7b		Opening the kitchen cabinet to take out the tablecloth. Closing the cabinet.
	2	32	8		Placing the tablecloth on the table.
202	3	-	2		Opening the kitchen cabinet.
	4	6, 10	2, 8		Taking a plate and a glass from the kitchen cabinet, and leaving them on the table.
	5	-	2		Closing the kitchen cabinet.
	6	2, 3, 31	7a, 8		Opening the drawer to take out a fork, a knife and a napkin, and leaving them on the table.
203	7	21, 30	3a, 8		Picking up an oil cruet and a salt-shaker from the shelf and leaving them on the worktop.
	8	22	1, 8		Opening the fridge to take out a jug of water. Closing the fridge and leaving the jug on the table.
	9	8	1, 8		Opening the fridge to take out a bowl. Closing the fridge and leaving the bowl on the table.
R	**ID**	**OBJ.**	**SC.**	**S**	**CLEARING THE TABLE AND WASHING THE DISHES**
204	10	10	5, 8		Taking the glass from the table to leave it in the sink.
	11	22	1, 5, 8		Taking the jug of water from the table to fill it with water from the tap. Carrying the jug to the fridge, opening the fridge to leave it inside. Closing the fridge door.

	12	21, 30	3a, 8		Taking the oil cruet and the salt-shaker from the table to leave them on the shelf.
205	13	3, 6	8		Taking the plate and the knife from the table.
	14	3, 6	5, 8		Throwing the leftovers on the plate (simulated) into the rubbish bin, with the help of the knife.
	15	3, 6	5		Leaving the plate and the knife in the sink.
206	16	2, 8	8		Taking the bowl and the fork from the table.
	17	2, 8	5, 8		Throwing the leftovers (simulated) into the rubbish bin, with the help of the fork.
	18	2, 8	5		Leaving the bowl and the fork in the sink.
207	19	32	8		Removing the tablecloth from the table, carrying it to one side of the room and shaking it.
	20	32	-		Folding the tablecloth.
	21	32	7b		Opening the kitchen cabinet to put the tablecloth away, and closing the cabinet.
208	22	36	5		Opening a bottle of washing-up liquid.
	23	34, 36	5		Taking the bottle of washing-up liquid and a dish sponge, and pouring (simulated) liquid onto the dish sponge.
	24	2, 3, 6, 8, 10, 34	5		Washing (simulated) the glass, the bowl, the plate, the fork and the knife with the dish sponge.
	25	2, 3, 6, 8, 10	4, 5		Rinsing (simulated) the plate, the bowl, the glass, the fork and the knife (in that order) with water, and leaving them on the small worktop.
209	26	8	2, 4		Taking the bowl, opening the kitchen cabinet and putting the bowl away inside it.
	27	10	2, 4		Taking the glass to put it away inside the kitchen cabinet.
	28	6, 33	2, 4		Taking the plate to dry it with a tea-towel.
	29	6	2, 4		Taking the dish to put it away inside the kitchen cabinet. Closing the kitchen cabinet.
	30	2, 3, 33	4		Taking the fork and the knife to dry them with the tea-towel.
	31	2, 3	4, 7a		Taking the fork and a knife and opening the drawer to put them away inside it. Closing the drawer.
210	32	35	5, 6		Taking a spray bottle to spray the worktop.
	33	33	5, 6		Taking the dishcloth to wipe the worktop.
	34	33	5		Cleaning the dishcloth under simulated water and wringing it out in the sink.
R	**ID**	**OBJ.**	**SC.**	**S**	**PREPARING AND DRINKING COFFEE**
Additional objects in scenarios: **Scenario 4 (Small worktop):** 4 (Dessertspoon). **Scenario 8 (Table):** 5 (Coffee spoon).					
211	35	45	3a		Taking a jar of ground coffee from a shelf and carrying it to the small worktop.
	36	45	4		Opening the jar of ground coffee.
212	37	37	4		Removing the handle of the coffee machine.
	38	4, 37, 45	4		Taking a dessertspoon and filling the handle of the coffee machine with coffee.
	39	37	4		Putting the handle of the coffee machine back in its place.
213	40	45	4, 3a		Closing the jar of ground coffee and placing it on the shelf.

	41	12	2, 4		Opening the kitchen cabinet and taking out a coffee cup. Closing the cabinet and putting the cup on the coffee machine.
	42	37	4		Switching on the coffee machine (Pressing a button).
214	43	20	3b, 4		Taking a tray from the shelf and leaving it on the worktop.
	44	12	4		Placing the coffee cup on the tray.
	45	24	3a, 4		Taking a sugar pot from the shelf and placing it on the tray.
	46	20	4, 8		Carrying the tray from the worktop to the table.
215	47	37	4		Removing the filter handle of the coffee machine.
	48	37	5		Throwing the used ground coffee into the rubbish bin.
	49	37	5		Leaving the filter handle of the coffee machine in the sink.
216	50	12, 24, 25	8	x	Opening the sugar pot, and putting a spoonful of sugar into the cup of coffee.
	51	5, 12	8	x	Picking up the spoon and stirring the coffee.
	52	12	8	x	Drinking (simulated) from the cup of coffee.
R	**ID**	**OBJ.**	**SC.**	**S**	**PREPARING A SIMPLE MEAL**
Additional objects in scenarios: **Scenario 6 (Worktop):** 6 (Dish), 8 (Medium-sized bowl), 9 (Small bowl). **Scenario 8 (Table):** 18 (Corkscrew).					
217	53	49	3b, 6		Picking up a bag of crisps from the shelf and carrying it to the worktop.
	54	49	6		Opening the bag of crisps.
	55	8, 49, 26	6		Putting the crisps into a bowl.
218	56	63	7a		Opening the drawer and taking out a sealing clip. Closing the drawer.
	57	49, 63	6		Closing the bag of crisps with the sealing clip.
219	58	48	3a, 6		Picking up a tin of olives from the shelf. Carrying it to the worktop.
	59	48	6		Opening the tin of olives.
	60	9, 48	6		Putting the olives into a little bowl.
	61	48	6, 5		Throwing the tin into the rubbish bin.
220	62	47	3a, 6		Picking up a jar of salted biscuits from the shelf. Carrying it to the worktop.
	63	47	6		Opening the jar of biscuits.
	64	6, 47	6		Putting biscuits on a plate.
	65	47	6		Closing the jar.
221	66	6	6, 8		Carrying the plate of biscuits from the worktop to the table.
	67	-	-		---- Displacement without manipulation ----
	68	8, 9	6, 8		Carrying the bowls from the worktop to the table.
222	69	59	3b, 8		Picking up a bottle of wine from the shelf and carrying it to the table.
	70	18, 59	8		Opening the bottle of wine with the corkscrew.
	71	18	8		Unscrewing the cork from the corkscrew.
	72	18	8		Folding the corkscrew.

223	73	13	2, 8		Opening the kitchen cabinet to pick up a wine glass, and carrying it to the table.
	74	-	8		Sitting in the chair at the table.
224	75	13, 59	8	x	Pouring wine from the bottle into the glass.
	76	13	8	x	Drinking (simulated) from the glass of wine.
225	77	64	8	x	Picking up one olive from the little bowl and eating (simulated) it, twice.
	78	26	8	x	Picking up a crisp from the bowl and eating (simulated) it.
	79	65	8	x	Picking up a biscuit from the dish and eating (simulated) it.

Appendix IV

This appendix contains tables with the task groups considered in the analyses performed in section 4.2 (An analysis of hand kinematics in feeding and cooking tasks).

G1: Transportation: open space

E	ID	PREPARING AND HAVING BREAKFAST
A	2	Taking the bag of sliced bread from the shelf and leaving it on the worktop.
	5	Taking the slice of bread out of the toaster and putting it on the plate.
	7	Carrying the plate from the worktop to the table.
	8	Taking the box of biscuits from the shelf and carrying it to the table.
		PREPARING, BAKING AND EATING A CAKE
	38	Taking a jar of flour from a shelf and carrying it to the worktop.
	40	Taking a bag of sugar and a box of baking powder from a shelf, and carrying them to the worktop.
	53	Taking a grater from a shelf and carrying it to the worktop.
	68	Taking a baking tray from the shelf and carrying it to the worktop.
	77	Taking the spatula, the knife and the bowl from the worktop and putting them in the sink.
	79	Taking the glass and the grater from the worktop, putting them in the sink.
	83	Taking the jar of flour from the worktop, carrying it to the shelf. Leaving the jar on the shelf.
	85	Taking the bag of sugar and the box of baking powder from the worktop, carrying them to the shelf. Leaving the objects on the shelf.
		PREPARING OMELETTES
	90	Taking the frying pan and its lid from a shelf and carrying them to the hob.
B		**SETTING THE TABLE**
	7	Picking up an oil cruet and a salt-shaker from the shelf and leaving them on the worktop.
		CLEARING THE TABLE AND WASHING THE DISHES
	10	Taking the glass from the table to leave it in the sink.
	12	Taking the oil cruet and the salt-shaker from the table to leave them on the shelf.
	13	Taking the plate and the knife from the table.
	15	Leaving the plate and the knife in the sink.
	16	Taking the bowl and the fork from the table.
	18	Leaving the bowl and the fork in the sink.
		PREPARING AND DRINKING COFFEE
	35	Taking a jar of ground coffee from a shelf and carrying it to the small worktop.
	43	Taking a tray from the shelf and leaving it on the worktop.
	44	Placing the coffee cup on the tray.
	45	Taking a sugar pot from the shelf and placing it on the tray.
	46	Carrying the tray from the worktop to the table.
	49	Leaving the filter handle of the coffee machine in the sink.
		PREPARING A SIMPLE MEAL
	53	Picking up a bag of crisps from the shelf and carrying it to the worktop.
	58	Picking up a tin of olives from the shelf. Carrying it to the worktop.
	62	Picking up a jar of salted biscuits from the shelf. Carrying it to the worktop.
	66	Carrying the plate of biscuits from the worktop to the table.
	68	Carrying the bowls from the worktop to the table.
	69	Picking up a bottle of wine from the shelf and carrying it to the table.

Table AIV.1: Tasks considered in group G1. "E" indicates experiment from the KINE-ADL BE-UJI Dataset, "ID" indicates the reference of the task within the experiment, following the numbering of the KINE-ADL BE-UJI Dataset.

G2: Transportation: closed space

	ID	PREPARING AND HAVING BREAKFAST
A	1	Opening the cabinet to take out the plate and leaving it on the worktop. Closing the cabinet.
	10	Opening the fridge, taking out a carton of milk and the apple, closing the fridge and carrying the objects to the table.
	11	Opening the fridge, taking out the jar of jam and the tub of butter, closing the fridge and carrying the objects to the table.
	12	Opening the cabinet, taking out the mug and the glass. Closing the cabinet and carrying the objects to the table.
	14	Taking a dessertspoon and a knife from the drawer. Closing the drawer. Carrying the objects to the table.
		PREPARING, BAKING AND EATING A CAKE
	35	Opening the kitchen cabinet, taking a bowl out, closing the cabinet and leaving the bowl on the worktop.
	37	Opening the fridge. Taking out a carton of eggs and a lemon. Closing the fridge. Carrying the objects to the worktop.
	41	Opening the fridge. Taking out a carton of milk, closing the fridge and carrying the milk to the worktop.
	43	Opening the kitchen cabinet, taking out a glass, closing the cabinet and carrying the glass to the worktop.
	48	Opening a drawer, taking out a fork and closing the drawer.
	59	Opening the drawer and taking out a pair of scissors. Leaving them on the worktop. Closing the drawer.
	72	Opening the oven, taking the tray from the worktop, putting it into the oven and closing it.
	73	Opening the oven, taking the tray out, leaving the tray on the kitchen worktop and closing the oven.
	74	Opening the drawer, taking out a knife and closing the drawer.
	80	Taking the carton of eggs and the lemon from the worktop, carrying them to the fridge, opening the fridge and putting the objects inside it. Closing the fridge.
	82	Taking the carton of milk from the worktop, carrying it to the fridge, opening the fridge and putting the carton inside it. Closing the fridge.
	86	Opening the oven, taking the tray with a 3kg weight on it from the worktop, putting it into the oven and closing it.
	87	Opening the oven, taking out a tray with a 3kg weight on it, leaving the tray on the worktop, closing the oven.
B		SETTING THE TABLE
	1	Opening the kitchen cabinet to take out the tablecloth. Closing the cabinet.
	4	Taking a plate and a glass from the kitchen cabinet, and leaving them on the table.
	6	Opening the drawer to take out a fork, a knife and a napkin, and leaving them on the table.
	8	Opening the fridge to take out a jug of water. Closing the fridge and leaving the jug on the table.
	9	Opening the fridge to take out a bowl. Closing the fridge and leaving the bowl on the table.
		CLEARING THE TABLE AND WASHING THE DISHES
	21	Opening the kitchen cabinet to put the tablecloth away, and closing the cabinet.
	26	Taking the bowl, opening the kitchen cabinet and putting the bowl away inside it.
	27	Taking the glass to put it away inside the kitchen cabinet.
	29	Taking the dish to put it away inside the kitchen cabinet. Closing the kitchen cabinet.

	31	Taking the fork and a knife and opening the drawer to put them away inside it. Closing the drawer.
		PREPARING AND DRINKING COFFEE
	41	Opening the kitchen cabinet and taking out a coffee cup. Closing the cabinet and putting the cup on the coffee machine.
	56	Opening the drawer and taking out a sealing clip. Closing the drawer.
	73	Opening the kitchen cabinet to pick up a wine glass, and carrying it to the table.

Table AIV.2: Tasks considered in group G2. "E" indicates experiment from the KINE-ADL BE-UJI Dataset, "ID" indicates the reference of the task within the experiment, following the numbering of the KINE-ADL BE-UJI Dataset.

G3: Opening and closing packages: unscrewing and screwing

		PREPARING AND HAVING BREAKFAST
A	16	Opening the cap of the carton of milk.
	18	Closing the carton of milk.
	23	Opening the bottle of juice.
	25	Closing the bottle.
B		**PREPARING AND DRINKING COFFEE**
	36	Opening the jar of ground coffee.
	40	Closing the jar of ground coffee and placing it on the shelf.

Table AIV.3: Tasks considered in group G3. "E" indicates experiment from the KINE-ADL BE-UJI Dataset, "ID" indicates the reference of the task within the experiment, following the numbering of the KINE-ADL BE-UJI Dataset.

G4: Opening and closing packages: other

	ID	PREPARING AND HAVING BREAKFAST
A	3	Opening the bag (initially closed with a sealing clip).
	6	Closing the bag of bread with the clip.
	20	Opening a box of biscuits and taking out the plastic tray.
	22	Pushing the tray back inside the box and closing the box.
	27	Opening the tub of butter.
	29	Closing the butter container.
	30	Opening the jar of jam.
	32	Closing the jar of jam.
		PREPARING, BAKING AND EATING A CAKE
	44	Opening the carton of eggs.
	47	Closing the carton of eggs.
	50	Opening the bag of sugar (initially closed with a peg).
	52	Closing the bag of sugar with the peg.
	55	Opening the jar of flour.
	58	Closing the jar of flour.
	63	Opening the box of baking powder, taking out one sachet and opening it. Pouring the powder into the bowl. Closing the box.
		PREPARING OMELETTES
	91	Taking a bottle of oil from the worktop, opening the cap, pouring oil into the pan, closing the bottle and leaving the bottle on the worktop.
B		**CLEARING THE TABLE AND WASHING THE DISHES**
	22	Opening a bottle of washing-up liquid.
		PREPARING A SIMPLE MEAL
	54	Opening the bag of crisps.
	57	Closing the bag of crisps with the sealing clip.
	59	Opening the tin of olives.
	63	Opening the jar of biscuits.
	65	Closing the jar.

Table AIV.4: Tasks considered in group G4. "E" indicates experiment from the KINE-ADL BE-UJI Dataset, "ID" indicates the reference of the task within the experiment, following the numbering of the KINE-ADL BE-UJI Dataset.

G5: Eating

	ID	PREPARING AND HAVING BREAKFAST
A	21	Taking out a biscuit, dipping it in the milk and eating the biscuit (simulated).
	33	Taking the slice of bread from the plate and biting it (simulated). Leaving it on the plate.
	34	Taking the apple, biting it twice (simulated), leaving it on the plate.
		PREPARING, BAKING AND EATING A CAKE
	76	Taking a piece of cake and biting it. Leaving the piece of cake on the worktop.
B		**PREPARING A SIMPLE MEAL**
	77	Picking up one olive from the little bowl and eating (simulated) it, twice.
	78	Picking up a crisp from the bowl and eating (simulated) it.
	79	Picking up a biscuit from the dish and eating (simulated) it.

Table AIV.5: Tasks considered in group G5. "E" indicates experiment from the KINE-ADL BE-UJI Dataset, "ID" indicates the reference of the task within the experiment, following the numbering of the KINE-ADL BE-UJI Dataset.

G6: Drinking

	ID	PREPARING AND HAVING BREAKFAST
A	19	Drinking from the mug (simulated).
	26	Drinking from the glass (simulated).
B		**PREPARING AND DRINKING COFFEE**
	52	Drinking (simulated) from the cup of coffee.
		PREPARING A SIMPLE MEAL
	76	Drinking (simulated) from the glass of wine.

Table AIV.6: Tasks considered in group G6. "E" indicates experiment from the KINE-ADL BE-UJI Dataset, "ID" indicates the reference of the task within the experiment, following the numbering of the KINE-ADL BE-UJI Dataset.

G7: Pouring

	ID	PREPARING AND HAVING BREAKFAST
A	17	Pouring milk from the carton into the mug.
	24	Pouring juice from the bottle into the glass.
		PREPARING, BAKING AND EATING A CAKE
	51	Taking the bag of sugar and filling the glass with sugar.
	56	Taking the jar of flour and filling the glass with flour.
	61	Taking the carton of milk and pouring milk into the glass.
	62	Taking the glass of milk and pouring it into the bowl.
	70	Pouring the cake dough onto the tray from the bowl using a spatula to scrape out all the dough.
		PREPARING OMELETTES
	91	Taking a bottle of oil from the worktop, opening the cap, pouring oil into the pan, closing the bottle and leaving the bottle on the worktop.
	93	Pouring the beaten eggs from the bowl into the pan, with the help of the fork.
	98	Taking the pan by the handle and putting the omelette on the plate.
B		SETTING THE TABLE
	14	Throwing the leftovers on the plate (simulated) into the rubbish bin, with the help of the knife.
	17	Throwing the leftovers (simulated) into the rubbish bin, with the help of the fork.
	23	Taking the bottle of washing-up liquid and a dish sponge, and pouring (simulated) liquid onto the dish sponge.
		PREPARING AND DRINKING COFFEE
	48	Throwing the used ground coffee into the rubbish bin.
		PREPARING A SIMPLE MEAL
	55	Putting the crisps into a bowl.
	60	Putting the olives into a little bowl.
	64	Putting biscuits on a plate.
	75	Pouring wine from the bottle into the glass.

Table AIV.7: Tasks considered in group G7. "E" indicates experiment from the KINE-ADL BE-UJI Dataset, "ID" indicates the reference of the task within the experiment, following the numbering of the KINE-ADL BE-UJI Dataset.

G8: Using cutlery and kitchen utensils

	ID	PREPARING AND HAVING BREAKFAST
A	28	Taking the knife and spreading butter on the slice of bread. Leaving the slice on the plate.
	31	Taking the dessertspoon and spreading jam on the slice of bread. Leaving the slice on the plate.
	ID	PREPARING, BAKING AND EATING A CAKE
	49	Beating the egg with the fork.
	57	Opening the drawer, taking out a spoon, closing the drawer. Taking two or three tablespoons of flour from the jar and pouring them into the glass.
	60	Taking the scissors to open the carton of milk and leaving them on the worktop.
	69	Picking up a spatula from a pot placed on the worktop.
	70	Pouring the cake dough onto the tray from the bowl using a spatula to scrape out all the dough.
	71	Spreading the cake dough on the tray with the spatula and leaving the spatula inside the bowl.
	75	Cutting a piece of cake with the knife. Leaving the knife on the worktop.
	ID	PREPARING OMELETTES
	88	Taking a fork from the worktop and beating eggs (simulated) in a bowl. Leaving the fork in the bowl.
	93	Pouring the beaten eggs from the bowl into the pan, with the help of the fork.
	94	Picking a slotted spoon from a pot on the worktop and stirring the contents of the pan.
	95	Taking the omelette out of the pan with the slotted spoon and placing it on a plate. Leaving the spoon on the worktop.
	99	Taking the knife from the worktop. Cutting the omelette in four pieces. Leaving the knife on the worktop.
B	ID	SETTING THE TABLE
	14	Throwing the leftovers on the plate (simulated) into the rubbish bin, with the help of the knife.
	17	Throwing the leftovers (simulated) into the rubbish bin, with the help of the fork.
	ID	PREPARING AND DRINKING COFFEE
	50	Opening the sugar pot, and putting a spoonful of sugar into the cup of coffee.
	51	Picking up the spoon and stirring the coffee.
	ID	PREPARING A SIMPLE MEAL
	70	Opening the bottle of wine with the corkscrew.
	71	Unscrewing the cork from the corkscrew.
	72	Folding the corkscrew.

Table AIV.8: Tasks considered in group G8. "E" indicates experiment from the KINE-ADL BE-UJI Dataset, "ID" indicates the reference of the task within the experiment, following the numbering of the KINE-ADL BE-UJI Dataset.

G9: Using appliances

	ID	PREPARING AND HAVING BREAKFAST
A	4	Taking out a slice of bread, putting it into the toaster and pushing down the toaster lever.
	ID	PREPARING, BAKING AND EATING A CAKE
	64	Taking the mixer from the worktop. Plugging it into a socket (with just one hand).
	65	Using the mixer to mix the ingredients in the bowl.
	66	Taking the mixer out of the bowl and leaving it on the worktop.
	67	Disconnecting the mixer from the socket (with just one hand).
	ID	PREPARING OMELETTES
	92	Switching the hob on.
B	ID	PREPARING AND DRINKING COFFEE
	37	Removing the handle of the coffee machine.
	38	Taking a dessertspoon and filling the handle of the coffee machine with coffee.
	39	Putting the handle of the coffee machine back in its place.
	42	Switching on the coffee machine (Pressing a button).
	47	Removing the filter handle of the coffee machine.

Table AIV.9: Tasks considered in group G9. "E" indicates experiment from the KINE-ADL BE-UJI Dataset, "ID" indicates the reference of the task within the experiment, following the numbering of the KINE-ADL BE-UJI Dataset.

G10: Cleaning

	ID	CLEARING THE TABLE AND WASHING THE DISHES
B	24	Washing (simulated) the glass, the bowl, the plate, the fork and the knife with the dish sponge.
	25	Rinsing (simulated) the plate, the bowl, the glass, the fork and the knife (in that order) with water, and leaving them on the small worktop.
	28	Taking the plate to dry it with a tea-towel.
	30	Taking the fork and the knife to dry them with the tea-towel.
	32	Taking a spray bottle to spray the worktop.
	33	Taking the dishcloth to wipe the worktop.
	34	Cleaning the dishcloth under simulated water and wringing it out in the sink.

Table AIV.10: Tasks considered in group G10. "E" indicates experiment from the KINE-ADL BE-UJI Dataset, "ID" indicates the reference of the task within the experiment, following the numbering of the KINE-ADL BE-UJI Dataset.

G11: Opening and closing cabinets, drawers and moving chairs

	ID	PREPARING AND HAVING BREAKFAST
A	13	Opening the drawer.
	15	Pulling the chair from under the table and sitting on the chair
B	ID	SETTING THE TABLE
	3	Opening the kitchen cabinet.
	5	Closing the kitchen cabinet.
	ID	PREPARING A SIMPLE MEAL
	74	Sitting in the chair at the table.

Table AIV.11: Tasks considered in group G11. "E" indicates experiment from the KINE-ADL BE-UJI Dataset, "ID" indicates the reference of the task within the experiment, following the numbering of the KINE-ADL BE-UJI Dataset.

G12: Displacement without manipulation

	ID	PREPARING AND HAVING BREAKFAST
A	9	*****Displacement without manipulation.
	ID	PREPARING, BAKING AND EATING A CAKE
	36	*****Displacement without manipulation.
	39	*****Displacement without manipulation.
	42	*****Displacement without manipulation.
	78	*****Displacement without manipulation.
	81	*****Displacement without manipulation.
	84	*****Displacement without manipulation.
B	ID	PREPARING A SIMPLE MEAL
	67	---- Displacement without manipulation ----

Table AIV.12: Tasks considered in group G12. "E" indicates experiment from the KINE-ADL BE-UJI Dataset, "ID" indicates the reference of the task within the experiment, following the numbering of the KINE-ADL BE-UJI Dataset.

G13: Other

	ID	PREPARING, BAKING AND EATING A CAKE
A	45	Breaking an egg into the bowl.
	46	Throwing the eggshell into the rubbish bin.
	54	Taking the lemon and the grater and grating the lemon into the bowl.
	ID	PREPARING OMELETTES
	89	Opening the salt container (placed on the worktop), taking salt with the tips of the fingers and pouring it into the bowl.
	96	Taking the pan lid from the worktop, putting it over the pan and turning the omelette over with the lid.
	97	Grasping the handle of the pan and shaking it.
B	ID	SETTING THE TABLE
	2	Placing the tablecloth on the table.
	ID	CLEARING THE TABLE AND WASHING THE DISHES
	11	Taking the jug of water from the table to fill it with water from the tap. Carrying the jug to the fridge, opening the fridge to leave it inside. Closing the fridge door.
	19	Removing the tablecloth from the table, carrying it to one side of the room and shaking it.
	20	Folding the tablecloth.
		PREPARING A SIMPLE MEAL
	61	Throwing the tin into the rubbish bin.

Table AIV.13: Tasks considered in group G13. "E" indicates experiment from the KINE-ADL BE-UJI Dataset, "ID" indicates the reference of the task within the experiment, following the numbering of the KINE-ADL BE-UJI Dataset.

Appendix V

This appendix contains tables with data corresponding to the analyses performed in section 5.3 (Effect of assistive devices on hand kinematics). This tables were presented as supplementary material in the original publication in the journal PeerJ. Specifically, the tables present:

- *Mean (SD) of the mean angles of each joint and task when performed with normal products and ADs (along with statistically significant differences marked).*

- *Mean (SD) of the range of motion (ROM) of each joint and task when performed with normal products and ADs (along with statistically significant differences marked).*

- *Mean (SD) of the median velocity of each joint and task when performed with normal products and ADs (along with statistically significant differences marked).*

- *Mean (SD) of the 95th percentile velocity of each joint and task when performed with normal products and ADs (along with statistically significant differences marked).*

	IP1_F	MCP1_F	CMC1_F	CMC1_A	PalmAr	MCP2_F	MCP3_F	MCP4_F	MCP5_F	MCP2-3_A	MCP3-4_A	MCP4-5_A	PIP2_F	PIP3_F	PIP4_F	PIP5_F
T1	-13.0 (18.1)	-3.0 (7.5)	15.7 (15.3)	15.2 (3.5)	15.5 (7.9)	21.9 (10.5)	22.9 (10.4)	15.2 (11.9)	22.0 (12.0)	3.4 (4.4)	8.3 (3.7)	-0.3 (4.4)	50.4 (11.3)	43.2 (9.4)	41.5 (11.7)	28.9 (13.7)
T2	-14.1 (13.4)	-2.7 (6.0)	12.5 (14.4)	13.1 (1.9)	16.4 (10.4)	25.1 (9.9)	33.4 (11.2)	20.5 (11.1)	23.3 (12.4)	5.6 (4.2)	8.3 (2.5)	-0.1 (3.8)	44.3 (8.5)	48.6 (4.8)	56.0 (9.3)	50.1 (11.8)
T3	8.2 (10.2)	-8.9 (6.1)	2.6 (13.5)	20.4 (2.9)	14.6 (9.1)	-5.4 (8.3)	12.6 (13.9)	13.8 (12.1)	18.5 (10.5)	20.3 (8.7)	14.0 (5.1)	5.1 (4.4)	28.0 (15.7)	34.4 (7.4)	30.6 (9.0)	22.9 (10.6)
T4	-17.5 (13.5)	-3.1 (10.3)	20.7 (15.1)	18.5 (2.4)	9.3 (8.0)	16.2 (8.1)	27.9 (11.2)	26.6 (10.2)	33.8 (8.4)	10.1 (8.6)	7.4 (2.9)	-1.4 (3.5)	50.7 (14.7)	49.3 (13.4)	42.5 (16.2)	29.5 (17.9)
T5	0.7 (9.1)	-7.2 (5.6)	15.3 (16.5)	18.8 (2.6)	14.1 (10.8)	9.6 (11.5)	23.1 (13.0)	13.7 (10.3)	22.5 (9.4)	7.8 (5.2)	9.6 (1.7)	0.5 (5.0)	45.1 (9.1)	35.4 (6.8)	32.7 (9.2)	23.9 (9.1)
T6	3.0 (10.5)	2.6 (7.5)	12.3 (14.5)	13.6 (2.7)	17.5 (11.3)	30.7 (9.7)	44.9 (11.7)	35.4 (9.7)	40.6 (11.2)	2.0 (4.3)	6.6 (3.2)	-3.9 (3.1)	51.4 (10.5)	48.9 (8.3)	59.0 (13.4)	52.3 (17.0)
T7	-11.2 (18.4)	6.4 (8.2)	19.2 (10.7)	14.3 (3.0)	5.4 (10.4)	35.5 (6.2)	38.7 (11.6)	29.0 (11.6)	40.6 (12.8)	2.5 (3.3)	8.3 (2.5)	-5.1 (4.1)	30.8 (16.6)	49.2 (7.9)	68.3 (8.0)	66.5 (7.6)
T8	-7.0 (8.4)	2.5 (7.1)	6.0 (11.1)	11.4 (1.8)	14.7 (10.2)	20.5 (8.5)	40.4 (9.8)	36.7 (9.7)	48.0 (11.0)	2.6 (5.6)	5.3 (3.2)	-5.7 (3.3)	46.1 (12.0)	47.2 (14.2)	55.4 (18.1)	52.6 (19.1)
T9	6.9 (9.3)	-12.9 (7.8)	-8.4 (13.2)	13.8 (2.8)	10.2 (11.4)	27.7 (11.1)	47.8 (11.4)	40.5 (9.1)	47.1 (8.9)	-0.9 (6.9)	1.8 (3.2)	-5.0 (4.2)	57.3 (7.3)	56.2 (8.0)	59.4 (9.0)	52.7 (8.8)
T10	-11.2 (16.4)	3.1 (5.9)	14.5 (11.5)	14.0 (1.7)	10.7 (8.1)	32.9 (5.7)	35.3 (8.2)	25.9 (9.1)	30.2 (11.4)	2.7 (4.6)	7.5 (2.2)	-0.5 (4.4)	33.9 (8.4)	54.2 (9.4)	63.4 (8.5)	56.4 (8.1)
T11	-18.0 (15.5)	3.7 (8.6)	11.8 (13.7)	13.5 (1.9)	12.5 (5.7)	30.0 (8.5)	39.6 (7.4)	28.6 (7.2)	28.8 (10.2)	1.0 (3.6)	5.7 (2.6)	-0.7 (3.2)	54.0 (9.6)	58.9 (12.6)	68.4 (13.6)	55.4 (16.9)

Table AV.1: Mean (SD) of the mean angle (deg) for each joint and task performed with normal products. *Joints, tasks and products labelled as in Figure 5.3.3. Positive values for flexion, abduction of fingers and palmar deviation of thumb.*

		IP1_F	MCP1_F	CMC1_F	CMC1_A	PalmAr	MCP2_F	MCP3_F	MCP4_F	MCP5_F	MCP2-3_A	MCP3-4_A	MCP4-5_A	PIP2_F	PIP3_F	PIP4_F	PIP5_F
T1	**A1**	-4.9 (28.0)	-0.7 (10.5)	13 (13.7)	15.3 (3.8)	▼6.7 (12.1)	27.6 (7.1)	27.8 (14.9)	18.4 (16.9)	29.5 (20.5)	2.4 (4.2)	10.6 (2.6)	-0.5 (7.1)	35.1 (19.1)	▲57.6 (11.0)	▲66.1 (13.4)	▲58.8 (15.0)
T2	**A1**	-6.3 (10.4)	3.0 (5.3)	14.8 (14.2)	14.1 (1.6)	16.2 (7.6)	23.5 (9.1)	31.8 (9.9)	25.1 (7.5)	▲31.5 (6.8)	4.5 (3.3)	8.5 (3.3)	-0.2 (3.1)	45.4 (21.5)	45.5 (6.4)	▼44.2 (7.7)	▼31.3 (12.0)
	A2	-16.5 (17.0)	-1.9 (8.1)	16.6 (13.3)	13.3 (2.3)	15.2 (8.9)	22.0 (10.3)	▼28.4 (12.7)	19.0 (12.1)	26.4 (13.0)	6.5 (4.1)	9.3 (2.7)	-1.3 (3.6)	40.6 (7.0)	45.7 (6.3)	53.1 (10.8)	49.8 (12.5)
T3	**A1**	▼-5.7 (12.8)	-14.1 (7.9)	-3.3 (16.0)	▼12.0 (2.3)	10.6 (8.6)	▲35.4 (10.5)	▲49.4 (11.4)	▲44.6 (8.3)	▲53.6 (6.7)	▼8.9 (5.6)	▼7.9 (3.4)	▼-4.9 (3.8)	▲71.1 (25.6)	▲78.6 (7.5)	▲78.7 (7.1)	▲62.0 (9.5)
T4	**A1**	▲7.5 (17.3)	-4.6 (11.5)	▼-8.4 (17.5)	▼14.6 (3.5)	7.2 (7.9)	▲40.6 (11.0)	▲49.6 (11.6)	▲40.3 (9.8)	43.4 (11.5)	▼1.0 (4.2)	5.0 (3.7)	-3.4 (3.5)	▲75.4 (8.5)	▲78.6 (10.4)	▲86.1 (9.5)	▲70.6 (11.7)
T5	**A1**	-12.1 (18.0)	-3.2 (8.6)	11.1 (17.0)	▼12.5 (2.8)	14.9 (10.3)	▲25.7 (17.7)	▲37.4 (16.0)	▲27.3 (18.8)	34.2 (20.7)	5.5 (7.0)	▼7.5 (1.8)	-2.2 (7.0)	▲72.1 (11.6)	▲68.6 (13.7)	▲69.0 (15.3)	▲58.1 (11.3)
T6	**A1**	-2.4 (16.0)	-0.6 (11.2)	6.4 (13.0)	15.2 (2.7)	▼9.0 (12.7)	29.0 (10.1)	▼33.9 (14.6)	30.7 (13.0)	39.7 (12.5)	5.3 (5.4)	▲9.1 (3.1)	-4.2 (3.2)	▼30.5 (17.3)	54.3 (12.0)	63.6 (9.9)	61.1 (11.6)
	A2	11.8 (14.3)	-2.4 (8.5)	6.5 (15.2)	14.8 (2.7)	▼8.4 (11.4)	30.9 (10.5)	▼31.6 (16.7)	30.2 (14.2)	42.0 (13.6)	3.5 (5.0)	▲9.8 (4.3)	-4.5 (4.5)	▼28.9 (16.7)	56.6 (14.2)	63.9 (10.7)	59.8 (9.8)
	A3	-7.0 (21.6)	0.5 (10.6)	10.9 (14.1)	▲16.1 (2.7)	▼9.7 (12.7)	27.0 (7.9)	▼29.8 (15.3)	▼21.7 (14.9)	28.6 (16.7)	4.6 (5.0)	▲8.6 (2.1)	-1.2 (5.4)	▼34.8 (14.8)	51.5 (9.5)	58.8 (11.4)	54.7 (12.4)
T7	**A1**	-5.3 (9.1)	▼-0.6 (10.2)	▼10.1 (13.3)	15.3 (1.6)	7.0 (11.5)	▼29.0 (7.9)	35.5 (11.9)	33.5 (13.2)	43.0 (16.2)	▲5.9 (4.0)	7.7 (3.0)	-4.4 (4.7)	28.6 (18.0)	53.3 (12.8)	62.0 (10.0)	▼56.2 (11.1)
	A2	1.1 (14.7)	▼-1.0 (9.6)	▼12.0 (10.7)	14.9 (2.1)	7.2 (10.9)	▼28.9 (6.0)	34.8 (12.4)	32.9 (13.2)	41.1 (14.9)	4.4 (4.0)	7.5 (2.8)	-3.9 (4.6)	31.4 (11.6)	52.3 (11.0)	60.3 (10.2)	▼53.8 (11.2)
	A3	-4.4 (15.2)	▼-0.7 (11.8)	▼12.3 (9.4)	▲16.3 (2.1)	5.0 (9.8)	▼27.3 (8.5)	▼31.9 (13.2)	26.7 (14.1)	37.3 (17.5)	▲7.2 (4.5)	8.2 (2.9)	-3.7 (4.7)	28.2 (15.4)	47.0 (10.4)	▼57.6 (8.1)	▼52.3 (8.3)
T8	**A1**	▲9.7 (14.6)	▼-6.1 (7.2)	1.2 (12.7)	▲16.2 (1.8)	▼4.0 (8.1)	▲28.5 (8.5)	39.9 (11.8)	35.6 (11.5)	46.4 (11.0)	5.7 (5.4)	▲7.4 (3.8)	-4.7 (2.8)	54.5 (13.6)	▲61.9 (7.0)	64.9 (7.4)	56.2 (7.3)
T9	**A1**	3.4 (18.3)	-8.0 (6.4)	▲6.3 (14.1)	17.0 (3.6)	10.6 (7.3)	23.7 (16.3)	▼37.9 (15.7)	▼28.6 (11.8)	▼33.2 (11.6)	▲6.6 (4.3)	▲8.2 (2.8)	▲-0.6 (3.4)	59.6 (8.8)	53.8 (7.6)	▼51.0 (8.0)	▼35.4 (9.3)
T10	**A1**	-10.1 (12.4)	▼-1.7 (5.5)	13.0 (13.7)	14.8 (1.5)	12.3 (7.3)	▼22.0 (9.9)	32.7 (11.9)	25.7 (10.3)	31.2 (9.7)	▲6.6 (6.0)	▲9.1 (2.6)	-0.3 (3.7)	41.1 (12.3)	50.9 (8.3)	▼53.2 (10.0)	▼41.9 (9.2)
T11	**A1**	-13.6 (14.3)	2.0 (7.0)	13.2 (9.6)	14.0 (2.0)	12.0 (11.5)	28.9 (7.1)	38.4 (8.4)	28.3 (7.7)	31.9 (9.5)	▲3.9 (2.9)	▲7.0 (2.5)	-1.3 (3.2)	▼43.5 (11.2)	58.6 (11.6)	66.2 (14.7)	54.9 (16.6)
	A2	-15.8 (16.2)	2.5 (6.4)	10.9 (12.6)	13.6 (2.2)	11.5 (8.9)	30.6 (7.4)	36.4 (8.3)	27.2 (9.0)	29.2 (12.4)	2.0 (3.6)	6.3 (2.7)	-1.3 (4.1)	55 (7.6)	61.8 (13.5)	70.5 (14.6)	58.3 (18.4)

Table AV.2: Mean (SD) of the mean angles (deg) for each joint and task performed with ADs. *Statistically significant differences with standard products are indicated: ▲ for higher values when using ADs, ▼ for lower values when using ADs. Joints, tasks and products labelled as in Figure 5.5.3. Positive values for flexion, abduction of fingers and palmar deviation of thumb.*

	IP1_F	MCP1_F	CMC1_F	CMC1_A	PalmAr	MCP2_F	MCP3_F	MCP4_F	MCP5_F	MCP2-3_A	MCP3-4_A	MCP4-5_A	PIP2_F	PIP3_F	PIP4_F	PIP5_F
T1	50.9 (24.9)	18.8 (6.6)	34.2 (14.7)	14.7 (5.5)	26.1 (5.6)	38.9 (7.6)	42.4 (7.3)	34.0 (9.8)	38.5 (13.0)	13.5 (5.1)	9.4 (4.3)	11.0 (5.0)	69.9 (13.6)	61.8 (18.4)	60.9 (22.0)	51.5 (28.6)
T2	68.6 (21.3)	24.9 (8.1)	63.2 (24.3)	14.1 (2.8)	30.5 (9.5)	42.7 (11.9)	54.8 (11.4)	48.7 (7.9)	55.1 (10.4)	15.8 (3.8)	11.1 (2.7)	13.6 (4.9)	67.6 (10.2)	71.9 (13.1)	81.4 (17.2)	77.0 (23.9)
T3	35.4 (13.1)	14.7 (12.3)	23.1 (9.0)	15.3 (2.9)	13.8 (5.4)	30.3 (6.8)	26.1 (8.2)	28.1 (12.8)	26.9 (15.4)	24.4 (8.2)	13.0 (7.1)	8.5 (3.1)	25.2 (5.6)	28.6 (9.4)	28.4 (7.7)	24.7 (13.6)
T4	32.9 (16.1)	15.3 (5.2)	32.7 (8.9)	13.3 (3.5)	22.0 (5.8)	32.4 (9.2)	40.5 (16.9)	44.3 (15.7)	54.7 (15.5)	17.9 (8.5)	9.0 (3.0)	14.3 (5.3)	49.0 (10.0)	47.2 (11.5)	46.4 (14.3)	35.2 (19.7)
T5	19.8 (7.8)	10.6 (4.4)	27.4 (9.4)	14.5 (3.4)	20.9 (6.6)	20.6 (6.0)	27.4 (9.0)	20.9 (8.6)	39.4 (12.6)	10.5 (5.3)	8.9 (3.3)	12.2 (5.9)	38.5 (10.5)	33.0 (11.9)	36.6 (16.4)	35.6 (18.7)
T6	40.3 (19.3)	14.7 (6.3)	30.3 (10.1)	11.7 (4.4)	26.2 (10.0)	28.3 (7.2)	46.7 (12.7)	46.5 (13.9)	55.2 (14.9)	13.0 (5.8)	8.2 (1.7)	12.6 (2.8)	49.8 (12.6)	56.1 (12.5)	67.6 (14.4)	61.8 (21.2)
T7	37.4 (23.7)	18.4 (6.4)	30.7 (9.3)	10.7 (3.2)	23.0 (5.2)	31.6 (9.5)	38.7 (13.0)	39.0 (12.9)	52.7 (12.6)	10.9 (2.6)	7.9 (2.9)	14.2 (3.0)	48.3 (20.1)	52.3 (11.1)	73.2 (11.4)	74.4 (16.3)
T8	20.3 (13.5)	12.5 (4.7)	23.2 (9.8)	4.1 (2.0)	14.4 (5.7)	19.9 (8.7)	29.9 (12.6)	38.9 (12.4)	49.4 (13.9)	8.3 (4.8)	6.8 (2.7)	10.4 (3.2)	30.7 (14.2)	33.0 (17.0)	40.6 (17.2)	41.1 (18.9)
T9	37.6 (20.5)	21.2 (10.9)	31.2 (8.3)	7.6 (2.9)	16.8 (5.1)	32.6 (7.9)	47.1 (9.2)	48.2 (8.4)	53.9 (11.6)	12.1 (5.8)	11.9 (3.5)	10.5 (4.2)	45.0 (6.7)	42.5 (14.6)	45.9 (14.2)	40.5 (15.5)
T10	42.8 (16.1)	18.0 (5.1)	32.5 (13.1)	10.2 (3.2)	24.9 (6.8)	41.1 (7.9)	43.6 (7.1)	49.7 (11.3)	65.3 (14.5)	17.6 (4.5)	9.5 (2.2)	17.7 (5.8)	42.7 (14.1)	48.8 (8.6)	64.6 (10.9)	60.0 (13.4)
T11	70.0 (25.0)	21.5 (6.7)	32.7 (10.9)	9.7 (3.4)	22.4 (8.5)	30.6 (4.3)	38.8 (8.2)	39.8 (8.8)	42.0 (13.8)	15.6 (5.9)	10.1 (2.3)	10.0 (3.6)	46.4 (9.1)	47.5 (16.0)	55.1 (19.7)	46.1 (18.2)

Table AV.3: Mean (SD) of the ROM (deg) for each joint and task performed with normal products. *Joints, tasks and products labelled as in Figure 5.3.3. Positive values for flexion, abduction of fingers and palmar deviation of thumb.*

		IP1_F	MCP1_F	CMC1_F	CMC1_A	PalmAr	MCP2_F	MCP3_F	MCP4_F	MCP5_F	MCP2-3_A	MCP3-4_A	MCP4-5_A	PIP2_F	PIP3_F	PIP4_F	PIP5_F
T1	**A1**	50.6 (21.5)	22.9 (11.0)	31.4 (16.3)	13.2 (3.2)	25.3 (8.4)	33.3 (8.0)	37.6 (13.5)	40.5 (14.6)	52.4 (15.6)	13.4 (4.2)	10 (2.7)	15.8 (5.8)	▼46.3 (17.8)	55.1 (13.4)	67.7 (14.1)	65.1 (13.9)
T2	**A1**	50.7 (24.3)	29.2 (11.5)	▼40.1 (14.3)	12 (2.5)	27.7 (7.0)	37.1 (15.9)	45.4 (16.7)	45.9 (8.6)	52.8 (6.4)	20.9 (9.5)	11.6 (3.1)	12.8 (2.4)	58.6 (20.2)	▼58.5 (7.8)	▼63.3 (10.0)	▼54.3 (14.4)
	A2	56.9 (18.2)	24.6 (8.0)	52.7 (24.1)	14.3 (3.7)	28.3 (5.9)	33.3 (10.8)	50.8 (13.3)	52.0 (11.3)	60.3 (14.7)	18 (3.9)	12.4 (3.5)	14.7 (4.1)	59.1 (17.8)	67.1 (14.9)	76.1 (18.3)	78.8 (24.9)
T3	**A1**	19.7 (11.3)	15.8 (8.7)	25.1 (7.4)	▼8.7 (2.7)	12.8 (3.0)	38.6 (15)	▲52.1 (14.8)	▲54.2 (9.0)	▲64.4 (7.0)	▼11.4 (6.8)	▼6.5 (2.4)	12.4 (3.8)	▲72.8 (15.8)	▲77.7 (9.8)	▲82.4 (13.2)	▲64.6 (17.4)
T4	**A1**	35.3 (13.5)	20.1 (10.9)	26.2 (14.0)	▼9.2 (3.7)	16.3 (6.5)	42.4 (11.6)	52.5 (12.8)	51.7 (10.7)	54.5 (11.6)	▼8.2 (2.1)	7.3 (2.8)	11.4 (3.2)	▲68.0 (8.5)	▲75.8 (13.7)	▲87.9 (16.0)	▲73.1 (19.9)
T5	**A1**	33.1 (18.5)	14.9 (10.5)	24.9 (11.6)	▼8.1 (2.2)	17.5 (7.7)	30.2 (14.5)	▲38.4 (15.1)	▲38.5 (16.0)	45.1 (18.2)	9.8 (4.3)	6.0 (1.9)	11.2 (5.3)	▲68.3 (9.7)	▲68.9 (11.5)	▲73.2 (16.8)	▲64.4 (19.4)
T6	**A1**	▼22.5 (12.0)	15.4 (8.6)	25.5 (9.2)	10.4 (4.0)	20.6 (7.4)	27.2 (5.7)	▼34.6 (9.8)	39.1 (9.5)	47.7 (12.1)	12.7 (6.1)	7.6 (2.0)	11.3 (3.2)	▼29.5 (15.0)	50.4 (13.2)	64.6 (14.1)	62.3 (15.5)
	A2	30.2 (12.2)	12.9 (4.9)	22.2 (5.9)	10.9 (3.9)	18.1 (4.2)	28.9 (5.2)	▼34.3 (9.2)	40.1 (10.0)	48.9 (11.7)	12.2 (3.7)	9.4 (3.5)	10.9 (3.3)	▼32.2 (17.2)	48.1 (19.9)	60.0 (20.7)	59.6 (22.4)
	A3	31.8 (13.2)	16.1 (7.6)	25.5 (8.9)	11.2 (4.2)	17.0 (5.7)	23.0 (4.6)	▼31.1 (8.1)	▼30.9 (10.2)	43.0 (12.3)	13.1 (6.1)	6.6 (2.2)	11.6 (5.5)	▼33.7 (9.6)	45.1 (15.5)	54.9 (20.8)	54.5 (19.2)
T7	**A1**	27.3 (14.7)	14.2 (5.1)	29.0 (14.6)	11.3 (2.7)	22.1 (5.8)	26.1 (11.5)	37.5 (11.3)	45.3 (13.2)	52.5 (11.1)	13.9 (4.6)	8.8 (2.4)	13.1 (2.8)	40.5 (13.9)	51.7 (15.0)	64.7 (14.8)	▼60.3 (19.5)
	A2	26.5 (17.5)	15.2 (5.4)	25.6 (10.5)	11.9 (4.5)	19.7 (5.5)	25.5 (7.5)	36.4 (11.3)	45.1 (14.0)	52.2 (15.1)	13.8 (4.4)	8.7 (2.8)	12.0 (2.6)	40.1 (15.2)	52.1 (13.3)	66.4 (12.6)	▼62.0 (15.5)
	A3	26.7 (9.9)	16.9 (6.1)	23.8 (8.4)	13.0 (2.9)	20.3 (6.5)	28.8 (9.5)	31.3 (10.1)	33.7 (10.9)	46.3 (12.7)	▲18.0 (6.1)	7.6 (1.4)	▼11.0 (2.6)	41.0 (13.2)	51.5 (10.1)	▼63.6 (8.7)	60.8 (10.0)
T8	**A1**	▲35.1 (22.5)	17.0 (7.8)	21.5 (13.6)	8.1 (3.8)	▲24.3 (7.1)	▲33.3 (10.4)	▲47.7 (13.2)	▲48.3 (7.3)	52.4 (8.0)	12.3 (4.9)	9.0 (3.1)	9.9 (1.7)	42.1 (8.4)	38.2 (16.1)	38.4 (15.5)	33.8 (13.0)
T9	**A1**	32.5 (16.0)	16.4 (10.2)	25.6 (11.0)	9.7 (2.7)	16.3 (5.4)	37.2 (8.3)	43.4 (16.7)	40.7 (16.9)	42.9 (16.2)	8.9 (4.3)	▼6.2 (3.1)	7.3 (2.2)	43.1 (10.0)	36.3 (10.8)	▼33.9 (8.9)	▼21.8 (5.5)
T10	**A1**	38.8 (10.6)	19.8 (7.4)	32.5 (11.5)	10.8 (3.6)	24.7 (7.4)	39.8 (10.1)	44.3 (11.4)	50.2 (12.6)	60.6 (10.6)	18.4 (4.7)	9.4 (2.8)	▼14.2 (5.4)	47.2 (8.9)	▼39.7 (9.5)	▼42.6 (7.6)	▼38.9 (10.5)
T11	**A1**	60.3 (21.3)	24.4 (7.0)	32.8 (11.6)	9.8 (2.9)	▲30.8 (8.0)	33.6 (7.0)	49.3 (18.6)	45.9 (13.3)	48.8 (10.5)	17.8 (8.5)	9.8 (3.9)	10.2 (2.9)	51.2 (14.6)	50.0 (16.6)	54.5 (18.2)	53.8 (15.8)
	A2	53.7 (18.3)	18.5 (5.8)	30.4 (9.1)	10.2 (2.5)	24.5 (7.9)	30.5 (7.0)	44.2 (9.4)	44.1 (7.8)	44.3 (10.4)	16.2 (4.2)	10.1 (2.4)	11.6 (3.7)	54.3 (12.4)	55.4 (11.8)	61.3 (14.6)	50.3 (13.6)

Table AV.4: Mean (SD) of the ROM (deg) for each joint and task performed with ADs. *Statistically significant differences with standard products are indicated: ▲ for higher values when using ADs, ▼ for lower values when using ADs. Joints, tasks and products labelled as in Figure 5.3.3. Positive values for flexion, abduction of fingers and palmar deviation of thumb.*

	IP1_F	**MCP1_F**	**CMC1_F**	**CMC1_A**	**PalmAr**	**MCP2_F**	**MCP3_F**	**MCP4_F**	**MCP5_F**	**MCP2-3_A**	**MCP3-4_A**	**MCP4-5_A**	**PIP2_F**	**PIP3_F**	**PIP4_F**	**PIP5_F**
T1	8.7 (6.3)	3.8 (2.7)	12.5 (5.0)	2.6 (1.9)	9.4 (3.9)	11.1 (7.0)	14.4 (6.4)	9.9 (3.9)	8.2 (6.3)	6.5 (2.4)	4.3 (1.2)	4.7 (1.8)	21.9 (5.1)	15.6 (6.7)	11.5 (8.1)	9.5 (7.5)
T2	28.8 (10.5)	17.1 (4.6)	31.7 (6.7)	8.3 (1.6)	15.8 (5.9)	23.3 (5.2)	34.5 (7.1)	27.8 (4.9)	28.5 (9.0)	10.0 (1.6)	7.6 (1.7)	8.5 (2.3)	24.9 (7.9)	28.1 (7.8)	31.9 (10.2)	36.7 (12.4)
T3	0.4 (0.5)	0.4 (1.2)	2.4 (3.5)	0.1 (0.1)	2.2 (1.9)	0.5 (1.0)	0.6 (0.5)	0.9 (1.4)	1.2 (3.1)	1.0 (0.9)	1.3 (1.1)	1.0 (0.8)	0.1 (0.2)	0.4 (0.5)	0.2 (0.4)	0.3 (0.4)
T4	1.0 (2.6)	0.1 (0.2)	1.5 (1.4)	0.1 (0.1)	2.3 (2.3)	0.6 (0.6)	0.6 (1.1)	1.7 (4.2)	1.2 (1.9)	1.0 (0.7)	1.2 (1.5)	1.6 (2.1)	0.2 (0.3)	0.5 (0.7)	0.4 (0.4)	0.2 (0.3)
T5	0.4 (0.6)	0.1 (0.1)	1.9 (1.8)	0.1 (0.1)	3.1 (1.8)	0.5 (0.4)	0.8 (0.7)	0.9 (0.8)	1.3 (1.6)	0.7 (0.6)	1.0 (0.5)	2.1 (1.4)	0.2 (0.3)	0.3 (0.5)	0.4 (0.4)	1.0 (0.9)
T6	13.2 (9.2)	2.1 (1.6)	11.0 (5.4)	1.9 (2.3)	7.1 (5.2)	5.0 (5.4)	6.2 (5.2)	9.9 (6.3)	8.9 (6.5)	4.2 (2.9)	3.8 (1.5)	3.4 (1.1)	8.5 (10.8)	5.4 (6.1)	4.4 (4.9)	5.2 (4.5)
T7	8.3 (7.1)	2.7 (2.0)	11.1 (6.4)	1.4 (1.6)	8.5 (3.4)	5.6 (5.7)	3.5 (3.1)	6.1 (4.8)	7.3 (5.2)	4.5 (1.9)	3.6 (2.1)	3.4 (1.7)	5.0 (4.7)	4.3 (5.9)	3.6 (3.5)	7.1 (6.8)
T8	1.7 (3.1)	0.4 (0.3)	4.0 (3.4)	0.2 (0.2)	3.4 (2.0)	1.1 (1.2)	1.5 (1.8)	3.6 (4.5)	3.9 (3.7)	0.7 (0.4)	1.6 (0.9)	1.8 (1.3)	1.2 (1.4)	1.5 (2.4)	1.6 (1.9)	1.9 (2.1)
T9	1.3 (1.5)	1.7 (2.0)	6.5 (3.6)	0.6 (0.7)	3.4 (1.9)	2.0 (1.6)	3.4 (4.6)	2.7 (4.2)	2.5 (4.5)	1.2 (1.5)	1.7 (1.4)	1.1 (0.8)	1.2 (1.5)	1.6 (2.3)	1.2 (1.3)	2.1 (3.5)
T10	8.0 (5.2)	3.1 (3.8)	13.6 (5.2)	2.5 (2.3)	8.9 (5.5)	9.8 (5.2)	10.5 (6.3)	10.3 (4.9)	13.0 (7.7)	6.3 (3.1)	3.8 (0.9)	5.1 (1.7)	9.6 (6.4)	5.3 (6.7)	6.0 (6.9)	6.1 (6.7)
T11	24.0 (14.0)	9.8 (4.8)	15.6 (5.0)	2.5 (1.4)	9.2 (4.8)	11.6 (7.0)	12.1 (6.8)	13.4 (5.6)	12.1 (5.8)	6.3 (2.2)	5.2 (2.0)	4.4 (1.3)	17.1 (8.0)	10.1 (6.3)	9.8 (5.5)	8.7 (6.7)

Table AV.5: Mean (SD) of the median velocity (deg/s) for each joint and task performed with normal products. *Joints, tasks and products labelled as in Figure 5.3.3. Positive values for flexion, abduction of fingers and palmar deviation of thumb.*

.

		IP1_F	MCP1_F	CMC1_F	CMC1_A	PalmAr	MCP2_F	MCP3_F	MCP4_F	MCP5_F	MCP2-3_A	MCP3-4_A	MCP4-5_A	PIP2_F	PIP3_F	PIP4_F	PIP5_F
T1	**A1**	6.8 (6.6)	3.7 (4.4)	11.5 (6.8)	1.9 (2.1)	10.0 (2.7)	▼4.5 (4.1)	▼5.2 (4.8)	6.2 (5.6)	8.7 (6.7)	4.1 (2.2)	3.7 (2.2)	4.9 (2.4)	▼4.8 (6.8)	▼3.0 (4.0)	4.6 (6.0)	8.1 (8.8)
T2	**A1**	22.0 (13.0)	▼12.6 (6.3)	25.1 (7.7)	▼4.0 (2.5)	16.3 (4.7)	16.4 (7.4)	▼22.3 (11.7)	24.8 (11.1)	26.9 (10.0)	10.0 (4.3)	7.4 (1.9)	8.2 (2.3)	14.1 (11.2)	20.5 (13.2)	24.3 (10.5)	26.3 (9.6)
	A2	25.4 (7.3)	16.2 (4.9)	29.4 (9.5)	6.7 (2.5)	13.1 (5.6)	20.1 (6.6)	26.6 (7.5)	23.0 (6.6)	23.6 (8.3)	12.4 (3.4)	8.5 (2.7)	7.8 (1.4)	21.2 (7.7)	23.2 (8.5)	26.7 (8.6)	29.9 (10.1)
T3	**A1**	0.0 (0.0)	0.1 (0.1)	1.8 (1.6)	0.2 (0.2)	1.2 (2.0)	0.0 (0.0)	▼0.1 (0.2)	0.1 (0.1)	0.0 (0.1)	0.3 (0.3)	▼0.2 (0.2)	▼0.2 (0.2)	0.0 (0.1)	0.0 (0.0)	0.0 (0.0)	0.1 (0.2)
T4	**A1**	0.3 (0.8)	0.3 (0.8)	1.1 (2.9)	0.1 (0.3)	0.6 (1.0)	▼0.2 (0.4)	0.3 (0.6)	0.2 (0.4)	0.2 (0.2)	▼0.3 (0.5)	0.4 (0.7)	0.3 (0.4)	0.1 (0.3)	0.0 (0.1)	0.0 (0.1)	0.1 (0.2)
T5	**A1**	0.5 (0.8)	0.3 (0.5)	2.6 (2.3)	0.2 (0.2)	2.3 (2.5)	0.3 (0.3)	0.3 (0.4)	0.7 (0.8)	1.2 (1.5)	0.6 (0.7)	0.6 (0.6)	1.3 (1.3)	0.2 (0.4)	0.2 (0.4)	0.3 (0.5)	0.6 (0.8)
T6	**A1**	▼2.3 (3.4)	0.6 (0.7)	6.0 (3.5)	0.6 (0.7)	5.6 (2.5)	2.2 (2.4)	5.0 (4.7)	5.1 (6.0)	5.8 (6.7)	3.6 (1.9)	2.9 (1.1)	2.5 (1.3)	1.1 (2.4)	0.9 (1.5)	0.4 (0.3)	1.2 (1.4)
	A2	▼2.9 (2.7)	▼0.5 (0.4)	▼5.1 (2.3)	0.4 (0.6)	4.9 (2.2)	2.1 (2.1)	4.1 (4.7)	5.5 (4.7)	3.7 (4.8)	3.8 (1.6)	3.1 (0.9)	2.8 (1.2)	1.1 (2.0)	0.3 (0.3)	0.5 (0.4)	▼0.6 (0.6)
	A3	▼3.5 (4.6)	2.0 (3.5)	▼5.0 (2.7)	0.4 (0.6)	5.7 (2.5)	1.8 (2.1)	4.6 (7.0)	4.8 (7.0)	5.2 (6.0)	3.0 (1.8)	2.3 (1.8)	2.4 (1.3)	1.1 (0.8)	0.6 (0.8)	0.6 (0.8)	1.9 (1.9)
T7	**A1**	3.7 (3.9)	▼1.1 (1.1)	9.8 (3.7)	0.7 (0.5)	8.3 (2.1)	2.9 (2.3)	4.1 (3.6)	6.3 (5.0)	4.5 (5.2)	4.5 (2.6)	4.0 (2.1)	3.0 (1.6)	3.0 (3.9)	1.4 (2.0)	1.1 (1.5)	3.2 (2.9)
	A2	3.4 (3.5)	1.1 (0.9)	7.9 (4.7)	0.8 (1.1)	7.6 (2.5)	4.2 (3.4)	3.6 (3.4)	6.0 (5.2)	4.8 (4.0)	4.3 (2.5)	3.5 (2.2)	2.6 (1.1)	3.9 (5.1)	1.9 (2.5)	2.5 (4.0)	3.4 (3.7)
	A3	4.4 (5.5)	2.2 (2.5)	10.5 (3.6)	1.3 (1.2)	7.8 (1.9)	3.4 (2.8)	2.8 (3.2)	▼2.2 (1.4)	▼2.4 (1.2)	4.6 (2.1)	3.1 (1.6)	3.0 (1.3)	3.4 (4.0)	3.2 (4.8)	3.6 (5.1)	4.7 (4.8)
T8	**A1**	1.7 (1.4)	0.8 (0.8)	4.0 (2.3)	0.2 (0.1)	3.3 (2.2)	1.6 (1.8)	1.7 (2.2)	1.7 (2.1)	1.4 (1.6)	1.6 (1.4)	1.4 (1.1)	0.9 (0.5)	0.9 (0.8)	0.3 (0.4)	0.1 (0.1)	0.4 (0.5)
T9	**A1**	1.6 (2.4)	0.5 (0.5)	5.2 (4.7)	0.4 (0.3)	2.2 (2.0)	2.2 (3.0)	2.9 (3.8)	2.3 (2.7)	2.8 (3.8)	0.9 (0.8)	1.3 (1.2)	1.6 (1.4)	0.7 (1.3)	0.3 (0.4)	0.5 (0.9)	1.1 (1.7)
T10	**A1**	9.2 (8.6)	3.9 (4.0)	12.7 (6.8)	2.2 (1.9)	8.8 (4.2)	8.4 (7.3)	10.4 (8.4)	9.0 (7.7)	8.6 (7.2)	5.9 (4.5)	3.6 (1.9)	3.6 (1.9)	6.6 (8.2)	4.1 (7.3)	3.8 (6.4)	5.7 (5.9)
T11	**A1**	▼16.2 (8.7)	8.6 (4.2)	14.5 (4.2)	3.0 (1.7)	9.3 (3.6)	9.0 (4.4)	11.7 (5.1)	11.7 (5.7)	10.3 (5.6)	6.4 (2.2)	4.8 (1.9)	3.9 (1.3)	▼10.2 (4.8)	7.7 (5.3)	6.6 (4.4)	7.5 (5.3)
	A2	19.6 (10.9)	8.2 (3.4)	16.8 (4.7)	3.3 (1.4)	8.3 (3.6)	10.2 (4.4)	13.5 (6.8)	14.0 (5.2)	11.3 (4.2)	7.3 (2.1)	4.9 (1.8)	4.0 (1.3)	16.7 (7.7)	9.6 (7.3)	7.5 (5.8)	8.7 (4.6)

Table AV.6: Mean (SD) of the median velocity (deg/s) for each joint and task performed with the ADs. *Statistically significant differences with standard products are indicated: ▲ for higher values when using ADs, ▼ for lower values when using ADs. Joints, tasks and products labelled as in Figure 5.3.3. Positive values for flexion, abduction of fingers and palmar deviation of thumb.*

	IP1_F	MCP1_F	CMC1_F	CMC1_A	PalmAr	MCP2_F	MCP3_F	MCP4_F	MCP5_F	MCP2-3_A	MCP3-4_A	MCP4-5_A	PIP2_F	PIP3_F	PIP4_F	PIP5_F
T1	100.1 (38.4)	38.7 (12.0)	58.8 (20.4)	21.1 (7.1)	47.0 (9.6)	72.8 (21.1)	71.8 (19.0)	58.0 (18.0)	53.4 (19.6)	37.1 (9.7)	20.1 (6.5)	21.1 (9.5)	126.1 (29.3)	92.2 (31.4)	88.2 (29.5)	65.8 (24.9)
T2	181.8 (59.8)	99.9 (30.7)	170.9 (61.1)	37.1 (8.6)	89.2 (21.3)	131.8 (37.5)	184.5 (38.4)	186.1 (45.8)	202.3 (44.3)	72.8 (26.8)	40.1 (11.5)	41.8 (13.4)	139.2 (30.1)	140.3 (43.9)	157.7 (57.2)	162.9 (74.0)
T3	61.0 (29.1)	28.0 (20.8)	40.5 (17.2)	19.8 (4.7)	29.6 (10.1)	64.1 (17.5)	60.7 (13.4)	45.1 (12.0)	36.7 (12.9)	29.6 (11.2)	22.1 (15.4)	18.6 (10.9)	42.7 (10.8)	50.1 (12.1)	52.1 (18.3)	56.8 (34.1)
T4	48.0 (19.9)	30.3 (8.6)	48.1 (16.3)	16.7 (3.7)	35.2 (11.6)	61.3 (23.2)	74.1 (39.6)	56.1 (20.2)	61.7 (20.3)	26.8 (7.8)	18.9 (4.9)	22.2 (7.9)	77.2 (33.0)	68.0 (23.9)	66.6 (19.8)	56.0 (24.4)
T5	35.0 (14.5)	22.0 (5.9)	47.2 (17.1)	18.5 (5.3)	37.6 (7.3)	43.9 (9.7)	56.9 (14.6)	39.7 (10.3)	58.8 (22.9)	18.1 (5.3)	17.9 (4.9)	22.9 (8.1)	53.5 (9.9)	46.1 (16.4)	57.9 (30.6)	63.9 (25.1)
T6	106.8 (47.3)	39.4 (14.2)	68.9 (21.7)	26.0 (8.9)	53.8 (15.0)	63.6 (28.2)	82.7 (27.3)	78.1 (27.7)	89.5 (30.4)	36.1 (16.9)	21.4 (5.0)	21.5 (4.2)	96.1 (29.3)	97.9 (33.7)	113.5 (40.7)	104.6 (38.0)
T7	83.5 (45.3)	38.8 (12.4)	71.8 (21.1)	19.6 (8.4)	65.2 (18.0)	77.3 (22.7)	81.0 (26.6)	84.7 (27.1)	103.0 (31.7)	40.0 (8.6)	25.5 (9.3)	29.4 (9.9)	125.6 (39.0)	96.2 (29.8)	134.3 (36.1)	146.3 (56.3)
T8	42.1 (28.7)	29.7 (9.6)	48.9 (19.1)	10.8 (3.0)	33.7 (10.7)	48.9 (15.4)	74.5 (23.1)	68.9 (22.4)	76.5 (25.7)	16.7 (4.8)	16.5 (4.9)	18.6 (6.1)	57.4 (28.7)	60.2 (23.6)	69.0 (27.7)	72.4 (34.9)
T9	92.7 (64.9)	36.4 (14.2)	63.5 (21.6)	15.4 (4.9)	35.5 (6.5)	69.0 (20.8)	85.8 (32.3)	86.9 (30.2)	88.2 (26.3)	23.7 (10.7)	22.7 (6.4)	17.8 (3.6)	88.8 (24.5)	60.5 (18.3)	69.1 (19.8)	69.8 (24.9)
T10	120.4 (40.1)	48.9 (15.5)	91.5 (38.3)	24.9 (8.4)	67.0 (24.1)	98.1 (22.0)	123.9 (30.0)	129.9 (48.6)	143.9 (47.9)	56.7 (25.5)	28.5 (10.3)	38.5 (13.0)	124.0 (25.2)	116.0 (34.5)	136.1 (34.3)	152.0 (37.4)
T11	156.1 (54.9)	62.6 (27.7)	80.1 (20.2)	26.8 (6.5)	51.5 (28.5)	81.5 (23.8)	99.0 (24.2)	95.8 (25.0)	81.6 (29.9)	46.9 (13.0)	25.8 (5.8)	21.1 (6.1)	135.6 (26.8)	112.5 (40.2)	119.5 (39.0)	81.5 (36.3)

Table AV.7: Mean (SD) of the P95 velocity (deg/s) for each joint and task when performed with normal products. *Joints, tasks and products labelled as in Figure 5.3.3. Positive values for flexion, abduction of fingers and palmar deviation of thumb.*

		IP1_F	MCP1_F	CMC1_F	CMC1_A	PalmAr	MCP2_F	MCP3_F	MCP4_F	MCP5_F	MCP2-3_A	MCP3-4_A	MCP4-5_A	PIP2_F	PIP3_F	PIP4_F	PIP5_F
T1	**A1**	111.3 (39.6)	44.0 (21.8)	73.8 (37.4)	22.5 (7.5)	57.3 (14. 3)	63.1 (16.6)	74.2 (18.0)	74.2 (20.3)	86.0 (34.6)	31.5 (10.1)	22.7 (7.8)	28.9 (8.6)	82.4 (35.9)	81.0 (13.8)	95.6 (22.0)	▲112.2 (49.1)
T2	**A1**	162.8 (78.5)	▼74.5 (35.0)	▼122.2 (51.3)	▼25.7 (6.8)	74.6 (19.2)	▼94.6 (36.3)	▼124.3 (45.5)	▼129.9 (50.1)	▼143.9 (50.0)	▼52.4 (19.2)	37.7 (14.0)	39.9 (11.3)	119.0 (40.6)	146.7 (54.8)	157.6 (45.3)	159.6 (44.9)
	A2	180.3 (52.0)	89.1 (17.5)	144.4 (54.2)	37.2 (11.1)	83.6 (14.5)	112.4 (30.5)	156.7 (29.9)	157.1 (42.8)	173.1 (37.5)	72.9 (23.4)	41.3 (13.5)	41.3 (8.4)	122.8 (33.5)	142.7 (17.5)	161.7 (23.7)	174.9 (51.7)
T3	**A1**	36.7 (12.9)	28.2 (9.8)	53.7 12.9)	▼15.9 (4.1)	32.3 (10.6)	78.5 (28.8)	▲103.2 (40.8)	▲95.7 (32.0)	▲97.6 (31.2)	▼20.7 (6.3)	18.4 (7.4)	21.5 (7.8)	▲115.5 (44.7)	▲110.7 (35.0)	▲119.4 (37.5)	▲98.6 (39.4)
T4	**A1**	60.0 (21.0)	41.1 (15.7)	51.6 (23.1)	16.2 (5.3)	30.9 (10.1)	65.0 (18.9)	79.4 (28.3)	67.2 (15.3)	68.5 (20.5)	▼18.2 (4.5)	15.3 (4.0)	18.6 (6.6)	89.1 (28.1)	▲95.2 (21.4)	▲113.1 (28.2)	▲96.5 (33.5)
T5	**A1**	51.1 (26.4)	25.9 (9.1)	46.2 (15.8)	16.6 (3.7)	36.2 (18.5)	58.2 (21.8)	64.4 (20.6)	55.1 (22.2)	61.2 (23.4)	16.8 (5.0)	13.8 (3.0)	22.3 (14.8)	▲92.8 (27.0)	▲93.7 (25.4)	101.9 (32.7)	89.1 (32.3)
T6	**A1**	▼60.4 (25.7)	39.5 (15.1)	▼51.6 (14.4)	▼17.7 (5.6)	48.2 (17.6)	52.8 (21.9)	▼63.1 (22.2)	62.9 (14.3)	▼69.9 (21.3)	31.8 (16.6)	21.9 (7.4)	21.1 (5.1)	▼62.2 (41.7)	95.2 (27.2)	111.7 (29.3)	110.3 (30.1)
	A2	▼59.9 (22.0)	29.4 (9.2)	▼51.5 (13.7)	18.8 (8.4)	47.4 (10.6)	58.6 (26.7)	▼70.3 (26.2)	63.9 (15.5)	▼68.2 (14.7)	33.6 (14.3)	21.8 (7.0)	22.3 (9.1)	▼58.0 (26.1)	94.1 (36.3)	116.2 (45.8)	112.6 (46.6)
	A3	▼62.7 (33.5)	38.9 (13.2)	▼50.2 (16.7)	▼16.9 (5.6)	46.9 (11.7)	57.2 (18.5)	70.1 (23.7)	60.6 (20.2)	74.5 (24.1)	32.8 (17.8)	18.9 (7.4)	23.7 (10.7)	▼67.0 (19.0)	90.7 (25.4)	106.5 (31.2)	103.0 (37.2)
T7	**A1**	80.5 (33.2)	38.7 (11.3)	66.9 (26.3)	20.0 (5.3)	62.8 (14.7)	▼60.6 (21.1)	75.1 (21.8)	77.4 (28.9)	89.7 (33.7)	34.9 (10.9)	26.0 (6.6)	28.4 (9.9)	120.2 (43.6)	115.1 (35.3)	126.3 (41.3)	▼113.3 (38.9)
	A2	72.1 (38.9)	33.8 (10.5)	63.6 (16.2)	19.4 (6.6)	58.2 (14.3)	63.5 (20.5)	76.5 (22.5)	75.9 (26.5)	83.3 (25.0)	39.7 (13.2)	28.2 (8.4)	26.3 (9.0)	▼94.8 (34.0)	115.9 (35.8)	136.0 (45.7)	127.5 (45.1)
	A3	95.7 (36.0)	41.4 (12.2)	68.0 (17.8)	26.0 (5.2)	68.5 (13.6)	83.3 (25.7)	97.0 (16.5)	83.0 (29.9)	91.0 (32.9)	45.9 (13.7)	28.8 (8.8)	27.2 (10.1)	131.6 (41.8)	▲134.9 (39.3)	136.2 (38.8)	124.5 (29.5)
T8	**A1**	▲83.4 (30.1)	36.9 (10.9)	54.3 (16.7)	14.4 (4.0)	▲50.9 (11.5)	▲89.8 (23.8)	▲107.5 (27.9)	89.6 (23.5)	79.3 (21.3)	▲34.5 (10.8)	▲23.5 (7.7)	21.3 (5.1)	▲94.8 (19.5)	78.2 (25.2)	83.3 (24.8)	89.1 (32.5)
T9	**A1**	64.4 (26.3)	35.5 (15.1)	62.7 (23.5)	17.2 (5.6)	35.5 (11.1)	96.6 (28.3)	121.2 (43.7)	97.9 (40.1)	92.9 (41.1)	21.6 (6.1)	16.0 (8.4)	19.1 (6.7)	101.9 (27.4)	▲88.4 (30.0)	83.9 (26.1)	59.4 (22.8)
T10	**A1**	128.2 (60.0)	43.8 (16.0)	77.7 (21.9)	23.0 (8.4)	56.5 (19.6)	92.2 (31.4)	107.5 (28.7)	103.7 (29.7)	120.0 (39.4)	57.4 (27.6)	28.4 (8.1)	35.0 (17.1)	103.6 (32.3)	▼86.3 (29.4)	▼100.0 (33.7)	▼107.0 (33.5)
T11	**A1**	146.7 (57.8)	67.2 (29.3)	82.6 (29.8)	24.9 (5.7)	63.9 (11.6)	89.2 (22.0)	98.8 (20.2)	96.1 (21.3)	91.1 (22.4)	57.1 (22.7)	25.9 (5.8)	22.3 (7.1)	116.1 (26.3)	114.5 (30.5)	114.3 (31.1)	104.9 (17.8)
	A2	143.5 (53.3)	55.8 (19.8)	83.7 (18.4)	31.1 (9.4)	48.4 (15.4)	78.1 (20.2)	117.3 (25.3)	110.0 (23.5)	90.9 (22.1)	46.7 (14.3)	26.1 (4.7)	23.1 (5.9)	137.2 (34.3)	135.3 (45.0)	130.1 (50.4)	97.4 (45.5)

Table AV.8: Mean (SD) of the percentile P95 values of velocities (deg/s) for each joint and task performed with the ADs. *Statistically significant differences with the standard products are indicated: ▲ for higher values when using ADs, ▼ for lower values when using ADs. Joints, tasks and products labelled as in Figure 5.3.3. Positive values for flexion, abduction of fingers and palmar deviation of thumb.*